REPORT DOCUMENTATION PAGE	Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
11 AUG 97

3. REPORT TYPE AND DATES COVERED

4. TITLE AND SUBTITLE
UTILIZING WIRELESS ATM OVER OFDM FOR A RURAL COMMUNICATIONS INFRASTRUCTURE

5. FUNDING NUMBERS

6. AUTHOR(S)
RITCHIE L. WEST

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITY OF COLORADO

8. PERFORMING ORGANIZATION REPORT NUMBER
97-106

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
DEPARTMENT OF THE AIR FORCE
AFIT/CI
2950 P. STREET
WRIGHT-PATTERSON AFB OH 45433-7765

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Does NOT include software

12a. DISTRIBUTION AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

19981130 041

DTIC QUALITY INSPECTED 4

14. SUBJECT TERMS

15. NUMBER OF PAGES
88

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

Utilizing Wireless ATM Over OFDM For A Rural Communications Infrastructure

by

Ritchie L. West

B.S.E.E., United States Air Force Academy, 1987

Technical Report EAS_ECE_1997_07

A thesis submitted to the University of Colorado in partial fulfillment of the requirements for the degree of

Master of Science

Department of Electrical and Computer Engineering

July 1997

This thesis for the Master of Science degree by

Ritchie L. West

has been approved for the

Department of Electrical and Computer Engineering

by

Mark A. Wickert

Mark A. Wickert, Chair

Rodger E. Ziemer

Rodger E. Ziemer

Chia-Jiu Wang

Chia-Jiu Wang

7/18/97

Date

West, Ritchie L., (M.S., Electrical Engineering)

Utilizing Wireless ATM Over OFDM For A Rural Communications Infrastructure

Thesis directed by Professor Mark A. Wickert

This thesis supports a project to implement a wireless ATM network utilizing OFDM for rural communities. In particular, this thesis explores the prospect of integrating the network into the mountain communities of Summit County, Colorado. There are many issues of the wireless environment that OFDM helps to combat and ATM appears to be a useful protocol for implementing present and future data requirements. This thesis presents a brief review of OFDM and a more in-depth review of ATM. The main focus of the thesis is a simulation model of a contention based reservation channel, connection admission control, and output buffering analysis. The results appear to support the conclusion that wireless ATM can support a vast mix of data requirements of today and tomorrow.

Acknowledgments

I would like to thank my instructors, Dr. Mark A. Wickert, Dr. Rodger E. Ziemer, and Dr. Chia-Jiu Wang for all of the help and patience they have shown me on my journey to this degree.

I would also like to thank all of the instructors at the EE department of the USAF Academy for their support. In particular I would like to thank LtCol Vantonningen and Maj Wright for their advice and support when things did not go as planned, and Col Klayton for giving me the chance to be here.

Finally, I owe my wife, Lisa, and my sons, James, Michael, and Andrew, and all the rest of my family and friends, a great debt of gratitude for putting up with me and the rocky road I have put us through to get to this point. I could have never done it without their love and support.

Contents

CHAPTER 1

1. INTRODUCTION 1

1.1. Overview of Wireless Networking 1

1.2. Purpose of Study 3
1.2.1. Multimedia capable communications for Rural Communities 3
1.2.2. Application towards Summit County--Integrator Corp. 4

1.3. Scope of Study 5
1.3.1. Non-mobile wireless ATM over OFDM 5
1.3.1.1. MAC using slotted ALOHA 5
1.3.1.2. CAC 6
1.3.1.3. Buffering Delays and Packet Loss 6

CHAPTER 2

2. OVERVIEW OF WIRELESS ATM 7

2.1. ATM Networks 7
2.1.1. Circuit Switching and Packet Switching 8
2.1.2. Virtual Channels and Virtual Paths 9
2.1.3. Quality of Service (QoS)--Central Admission Control (CAC) and Usage Parameter Control (UPC) 11
2.1.4. ATM Adaptation Layer 15
2.1.5. ATM packets 17

2.2. The Wireless Network 18
2.2.1. Multiple Access Techniques 18
2.2.1.1. FDMA 19
2.2.1.2. TDMA 19
2.2.1.3. CDMA 20
2.2.2. Duplexing 21
2.2.3. Medium Access Control (MAC) 21

2.3. Dealing with the Wireless Environment 23
2.3.1. Problems in the Environment 23
2.3.2. Orthogonal Frequency Division Multiplexing (OFDM) 24

2.4. Review of Previous Literature 25
2.4.1. Raychaudhuri--WATMnet 25
2.4.2. Acampora--antenna elements 27
2.4.3. Goodman--PRMA 27

CHAPTER 3

3. APPROACH AND SIMULATION DESIGN 29

3.1. The Summit County System 30
3.1.1. The Local Anchor/Tenant Network 30
3.1.2. The Backbone Network 31

3.2. Design Parameters and Considerations 32
3.2.1. Frequency allocation--Uplinks and Downlinks 33
3.2.2. The Contention Based Reservation Channel and Dynamic Allocation 34
3.2.3. ARQ/FEC and OFDM required overheads 35

3.3. Simulation Approach and Assumptions 36
3.3.1. ATM/OFDM conversion 36
3.3.2. Data generation 37
3.3.3. Reserved capacity and common capacity 37
3.3.4. Buffering and ATM cell delivery 39

3.4. Model Layout 40
3.4.1. GPSS fundamentals 40
3.4.2. Connection Requests and Timing Frame Generation 41
3.4.3. The ALOHA Based Reservation Channel—Model Part 1 42
3.4.4. The Local Area and Backbone Connection Setup—Model Part 2 44
3.4.5. Buffering on the Backbone—Model Sub Part 3 48

CHAPTER 4

4. RESULTS AND ANALYSIS 51

4.1. Reservation Channel--Slotted ALOHA vs Pure ALOHA 51
4.1.1. Theoretical results 51
4.1.2. Simulation results 54

4.2. Connection Admission Control 56
4.2.1. Theoretical results 56
4.2.2. Simulation results 61

4.3. Cell Loss--Buffering Results on the Backbone 69
4.3.1. Theoretical results 69
4.3.2. Simulation results 72

CHAPTER 5

5. CONCLUSIONS 74

5.1. Summary of Results 74

5.2. Areas for Further Research 75
5.2.1. Self-similar data traffic generation 75

5.2.2. Integration of mobile handoffs 76
5.2.3. Types of traffic and demand 76
5.2.4. The System Program 77

REFERENCES 78

APPENDIX

Details of Simulation Code 81
Reservation Channels 82
Slotted ALOHA 82
Pure ALOHA 84
Connection Admission Control 85
Backbone Buffering Analysis 86

List of Tables

Table 1: Possible Third Generation Applications [1] 2
Table 2: OSI Seven-Layer Model [9] 15
Table 3: ATM Header Fields [10] 17
Table 4: Network Data Traffic 37
Table 5: VPI Path Selection 45
Table 6: Predicted 2 Hour Run for Pure ALOHA 52
Table 7: Predicted 5 Hour Run for Pure ALOHA 53
Table 8: Predicted 2 Hour Run for Slotted ALOHA 53
Table 9: Predicted 5 Hour Run for Slotted ALOHA 54
Table 10: 2 Hour Pure ALOHA Results (Delay in ms) 54
Table 11: 5 Hour Pure ALOHA Results (Delay in ms) 54
Table 12: 2 Hour Slotted ALOHA Results (Delay in ms) 55
Table 13: 5 Hour Slotted ALOHA Results (Delay in ms) 55
Table 14: Cells/day Local Node Data Generation 58
Table 15: Local Node Total Capacity 58
Table 16: Number of Users to Percent Capacity 58
Table 17: Total Cells/Day Available per Link 60
Table 18: Cells/Day Utilized on each Link per User 60
Table 19: Number of Users per Link Capacity 61
Table 20: Total Network--1000 Users 62
Table 21: Total Network--2000 Users 62
Table 22: Total Network--3000 Users 63
Table 23: Total Network--4000 Users 63
Table 24: Total Network--5000 Users 64
Table 25: Total Network--10,000 Users 64
Table 26: Part 2 ABR Analysis--1000 Users 66
Table 27: Part 2 ABR Analysis--2000 Users 66
Table 28: Part 2 ABR Analysis--3000 Users 67
Table 29: Part 2 ABR Analysis--4000 Users 67
Table 30: Part 2 ABR Analysis--5000 Users 68
Table 31: Part 2 ABR Analysis--10,000 Users 68
Table 32: Buffer Link Analysis Total cells/day 70
Table 33: Buffer Analysis Cells/day for each Link per User 71
Table 34: Buffer Analysis Number of Users per Link Capacity 71
Table 35: Buffer Analysis Results 73

List of Figures

Figure 1: Topography of Summit County [4] ... 4
Figure 2: ATM Virtual Path and Virtual Channel Switching [8] ... 10
Figure 3: ATM Virtual Path and Virtual Channel Translations [8] ... 10
Figure 4: ATM Space Priority Buffer [7] ... 11
Figure 5: ATM Time Priority Buffer [7] ... 12
Figure 6: ATM Leaky Bucket [7] ... 14
Figure 7: ATM Service Classes and AAL Types [6], [9] ... 16
Figure 8: ATM Protocol Layering [7] ... 16
Figure 9: ATM HEC State Diagram [11] ... 17
Figure 10: FDMA Example [12] ... 19
Figure 11: TDMA Example [12] ... 20
Figure 12: OFDM Signal with 32 Carriers ... 24
Figure 13: Dynamic TDMA/TDD Control Frame [14] ... 26
Figure 14: Discrete Event Simulation Modeling Process [15] ... 30
Figure 15: Wireless Local Area Node [16] ... 31
Figure 16: Wireless Backbone/Local Network [16]. ... 32
Figure 17: Wireless Network Utilization of Frequency Band ... 34
Figure 18: Local Anchor/Tenant Capacity Pools ... 38
Figure 19: Model Topography for Local Anchor/Tenant and Backbone Data Traffic ... 44
Figure 20: Traffic Routing Effects on Node 1 ... 57
Figure 21: Traffic Affects on Link Capacity ... 59
Figure 22: Comparison of Calls Attempted and Calls Waited ... 65
Figure 23: Traffic Routing Effects on Buffer Link Analysis ... 70

Chapter 1

1. Introduction

1.1. Overview of Wireless Networking

Modern wireless communications are sometimes categorized as three different generations or stages of development. The first-generation can trace its roots to the first mobile telephone service introduced by AT&T in 1946 [1]. This first service was basically a mobile telephone connected to a radio transceiver. This transceiver would communicate with a powerful base station providing coverage up to 50 miles or more. This first generation suffered from call blocking problems due to a lack of available frequency bandwidth for multiple users. As late as 1970, only 12 mobile users at a time could be supported in New York City [1]. This helped to fuel the search for a better alternative and the alternative is currently cellular re-use of frequency bandwidth. Analog cellular technology (first-generation) is the dominant technology in place in most cities today. A larger number of users are able to be supported by geographically dividing the area into radio "cells" assigned portions of the total available frequency spectrum. Interference is avoided by ensuring that no adjacent cells are assigned the same portion. As the population increases, more cells and smaller cells can be added.

Larger cities are now beginning to offer the next step in wireless communications, second-generation cellular. This technology still uses the same cellular frequency re-use idea, but utilizes digital technology such as time division multiple access (TDMA) or code division multiple access (CDMA) to make more efficient use of the frequency

bandwidth. The digital approach enables users to enjoy higher quality connections with more wireline type telephone functions available. The higher efficiency of the digital cellular approach has an added benefit in that the user's hand unit is smaller, does not use as much power, and the battery can last much longer [1].

Third-generation technology will take this digital efficiency to new heights. There is already great interest in Personal Communications Services (PCS) as a kind of bridge between the two generations. PCS should be able to provide three key elements: An easy-to-use handset with many functions; A personal phone number which can follow the user anywhere; An individualized personal profile that follows the user and provides a customized set of functions at any location [1]. These systems will have a limited data capability that the third-generation will improve upon. Third-generation

Table 1: Possible Third Generation Applications [1]

Teleservices	**Throughput (kbs)**	**Target Bit Error Rate**
Telephony	8-32	10^{-3}
Teleconference	32	10^{-3}
Voice mail	32	10^{-3}
Program sound	128	10^{-6}
Video Telephony	64	10^{-7}
Video Conference	384-768	10^{-7}
Remote terminal	1.2-9.6	10^{-6}
User profile editing	1.2-9.6	10^{-6}
Telefax (Group 4)	64	10^{-6}
Voiceband data	64	10^{-6}
Database access	2.4-768.0	10^{-6}
Message broadcast	2.4	10^{-6}
Unrestricted digital information	64-1,920	10^{-6}
Navigation	2.4-64.0	10^{-6}
Location	2.4-64.0	10^{-6}

cellular technology will basically be a wireless extension of the Integrated Services Digital Network (ISDN) available on landlines. Some of these services include teleconferencing, videoconferencing, telefaxing, and data file access, see Table 1 [1].

It is possible that one day there will be a network of microcells and macrocells such that base stations may be installed on every light post, in every building, and even on aircraft and trains. This could enable such units to be used as navigation devices--small units in cars could be used to provide real time maps and at the same time, provide local information about restaurants, hotel vacancy status, entertainment news for whatever area the user is traveling through. This same third-generation technology can be applied on a larger scale in areas without as much infrastructure in place as there is in large cities.

1.2. Purpose of Study

1.2.1. Multimedia capable communications for Rural Communities

Rural communities are at a disadvantage to urban communities for access to the new technologies available for accessing information. These areas are often characterized by low population densities spread over a large area. Telecommunication businesses are usually slower to provide services in these areas since they can make more money in urban areas. Although research for third-generation wireless tends to focus on microcell environments, sometimes on the order of 100 meters for indoor environments [2], it is possible to apply the third-generation techniques on a large macrocell basis. These large macrocells can be connected through wireless channels as well to provide the versatile networking capabilities of third-generation requirements to rural communities. The main

advantage of using these wireless approaches is that they may provide an economically feasible way to give rural communities access to the National Information Infrastructure (NII). The Clinton administration has placed a top priority in developing an advanced NII that reaches into inner cities and rural communities. Problems with a relative decline in income, high unemployment, low workforce participation, and an exodus of talent could be addressed with third-generation technology's ability to reduce the barriers of distance and space that disadvantage rural areas [3].

1.2.2. Application towards Summit County--Integrator Corp.

This project is supporting a feasibility study in progress. Integrator Corporation is a small business that is trying to bring third-generation technology to rural communities. It is exploring the possible application of wireless macrocells connected by a wireless backbone channel in the communities of Summit County, Colorado. Summit County is a mountain community of small resort and mining towns which have the added complication of mountainous terrain to low populations and distance density. Figure 1 shows the general topology of Summit County. Integrator's vision is to use the asynchronous transfer mode (ATM) network protocol over

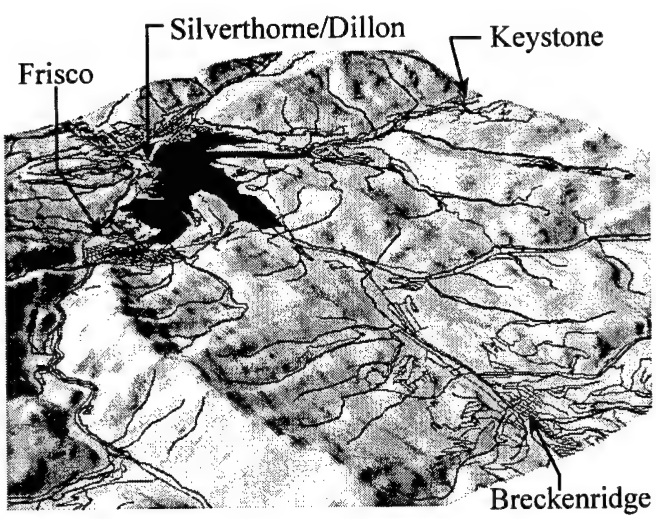


Figure 1: Topography of Summit County [4]

orthogonal frequency division multiplexing (OFDM) wireless channels. ATM is useful in that it is a very versatile protocol supporting a vast range of data rates that is typical of third-generation applications. OFDM is useful in that it is a robust technique that is resistive to many of the propagation problems inherent in the wireless environment. Ideally, users in the towns of Breckenridge, Frisco, Keystone, Silverthorne, and Dillon would be able to connect to a wireless base station in their town. These base stations will be situated at schools, hospitals, or other information focal points in their communities. The base stations are in turn connected to the other wireless base stations through a wireless backbone. One of these town's base stations would also be connected to the Public Switched Telephone Network (PSTN) in order to give the wireless network access to the rest of the world.

1.3. Scope of Study

1.3.1. Non-mobile wireless ATM over OFDM

This study will focus on the ATM aspect of the wireless network. OFDM will be briefly described in Chapter 2, and an OFDM block rate will be used to determine ATM packet rate. Otherwise, this analysis will be entirely related to ATM with some peculiarities of wireless applied. This study will not look into mobile wireless and will assume the users and the base stations are relatively stationary so issues concerning hand-offs, Doppler frequency shift, and station tracking will not affect the results.

1.3.1.1. *MAC using slotted ALOHA*

Medium access control (MAC) is investigated assuming a contention-based reservation channel is used. Two types of ALOHA are simulated, slotted ALOHA and

pure ALOHA with slotted ALOHA being the superior technique. Slotted ALOHA is assumed to be used in this network. Data is collected on the number of times a request has to be repeated before it successfully gets through.

1.3.1.2.CAC

Connection Admission Control (CAC) is extensively explored in this study. First a traffic profile and CAC is explored for one base node, then a full backbone network of four base nodes with one connected to the PSTN is explored. Since the reservation channel's affects upon the overall performance is minimal in comparison to the amount of offered traffic, the slotted ALOHA reservation channel is not applied in this section. Data is collected on the length of wait before a channel is assigned for different types of traffic at different loads.

1.3.1.3.Buffering Delays and Packet Loss

Finally an investigation of the affects of queueing buffers on the backbone network is made. Since these buffers affect mainly the traffic flowing between the nodes, this investigation focuses on the traffic on the backbone network and does not look at the local traffic at one node. Data is collected for the number of cells lost, the average delay of cells, and a comparison is made by data type and amount of network loading.

Chapter 2

2. Overview of Wireless ATM

The main focus of this thesis is ATM issues. This chapter will provide an in-depth review of ATM networks. It will also provide brief reviews of wireless issues and previous related literature.

2.1. ATM Networks

It became apparent in the late 1980s that the ISDN would probably not be versatile enough to handle the varied requirements of third generation applications. The International Telecommunications Union-Telecommunications Standards Sector (now known as the ITU-T, but was then the CCITT) helped to standardize a proposal known as Asynchronous Time Division (ATD). This proposal was later renamed to ATM and is characterized by a fixed packet size, fixed header pattern, a bit error rate of 10^{-10}, and a cell loss rate of 10^{-6}. ATM is able to overcome some of the limitations of ISDN by being able to provide bandwidth on demand and a guaranteed Quality of Service (QoS). ATM does this through the technique of statistical multiplexing, a combination of packet switched and circuit switched technologies, and the fixed packet size. ATM, with the QoS guarantees, is seen as the ultimate networking alternative on the desktop, in the Local Area Network (LAN), in the Metropolitan Area Network (MAN), and in the Wide Area Network (WAN) communities [5].

2.1.1. Circuit Switching and Packet Switching

The majority of today's PSTN follows either a circuit switching technology or a packet switching technology. A good example of circuit switching is a telephone connection. When a person attempts to make a call, a path is set up through the telephone network to the person receiving the call. Once this path is set up, it is a guaranteed path for the duration of the call--even if neither person does not talk for certain periods of time. This means that network bandwidth is wasted when neither person is talking. Packet switching technology makes full use of the bandwidth but can not guarantee real-time delivery like circuit switching technology can. Packet switching is able to do this by splitting the user's message into a collection of packets before sending the message onto the network. When the packets hit the network, each network switch makes a separate decision for each packet on which route is the fastest at that time. This means that packets from the same message can take a variety of different routes to their destination and are very likely to arrive out of order. The user's application must then put the packets back into the proper order when reconstructing the message. The most common protocol on the internet, Transmission Control Protocol/Internet Protocol (TCP/IP), uses this technology for transferring data. This process is unable to guarantee real time delivery necessary for such third generation applications as video conferencing, teleconferencing, and navigation. Circuit switching technology can guarantee the real time delivery, but frequently can not supply the necessary bandwidth for some of these applications. ATM takes advantage of both technologies through the use of virtual channels and virtual paths.

2.1.2. Virtual Channels and Virtual Paths

ATM uses a powerful routing technique known as virtual channel (VC) and virtual path (VP) logical routing. The ATM packet header includes a virtual channel identifier (VCI) and a virtual path identifier (VPI) that are used to identify the logical route the packet is to follow. The VC is a unidirectional transmission route for the ATM packets, whereas the VP is a collection of VCs sharing the same path [6]. A route of concatenated VCs establishes the link between the two users and is known as a virtual channel connection (VCC). VPs enable the network to set up a VCC without having to know the individual VCIs of each interconnection. This "logical" routing is very flexible in that new VPs can be created to handle expected changes in demand to different destinations without having to change the physical structure of the network [7]. This approach enables ATM switches to operate faster than other types of network switches.

There are two main types of ATM switches, a VP switch and a VC switch. The VP switch only needs to examine the VPI in the packet header, whereas the VC switch needs to examine both the VPI and the VCI. The use of VPs allows the switch to not have to examine the full routing field, which results in less overhead and processing delay. Figure 2 (a) shows an example of the same VCI being translated across four different VPs and three ATM switches, whereas Figure 2 (b) shows the same VPs, but now ATM switch B is a VC switch instead of a VP switch. This could be an example of two different networks connected by the VC switch with one network using VCI 14 and the other using VCI 23. This straight forward interface also involves relatively small lookup tables.

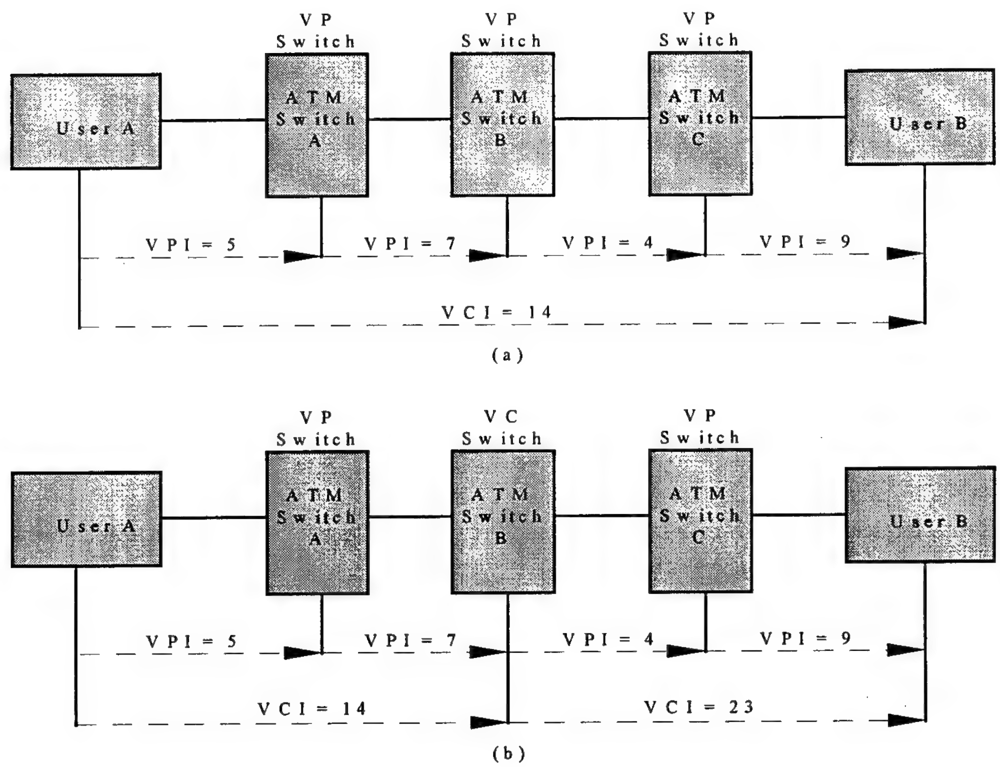


Figure 2: ATM Virtual Path and Virtual Channel Switching [8]

Figure 3 (a) shows an example of how VPIs are translated, but the VCIs remain

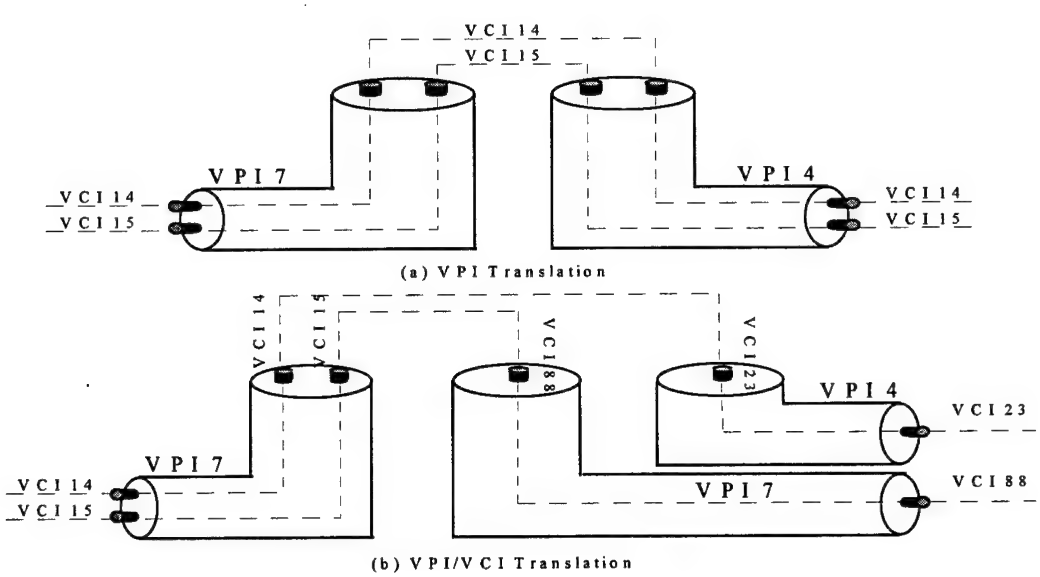


Figure 3: ATM Virtual Path and Virtual Channel Translations [8]

the same as would be the case with VP switch B of Figure 2 (a). Figure 3 (b) shows an example of where a VCI is changed as VCI 15 is mapped to VCI 88 from the incoming VPI 17 to the outgoing VP 17. It also shows an example of both a VCI and a VPI translation as would occur with the VC switch B of Figure 2 (b)--VCI 14 from incoming VP 7 is mapped to VCI 23 of outgoing VPI 4.

2.1.3. Quality of Service (QoS)--Central Admission Control (CAC) and Usage Parameter Control (UPC)

ATM switches use buffers to queue incoming packets since packets from multiple sources using the same VP or VC may arrive at the same time. Since only one packet may proceed in a given time slot on a given VC, the other packets that arrived at the same time must wait their turn in a buffer until they are allowed to proceed. These buffers normally employ one of two different priority mechanisms, space priority or time priority. Figure 4 shows an example of space priority. High priority cell number 6 arrives to find the buffer full, but there are two lower priority cells in the buffer. The priority mechanism forces out the last low priority cell in the buffer, since the buffer is first in-first out (FIFO) by priority, to make room for the high priority cell. Had there

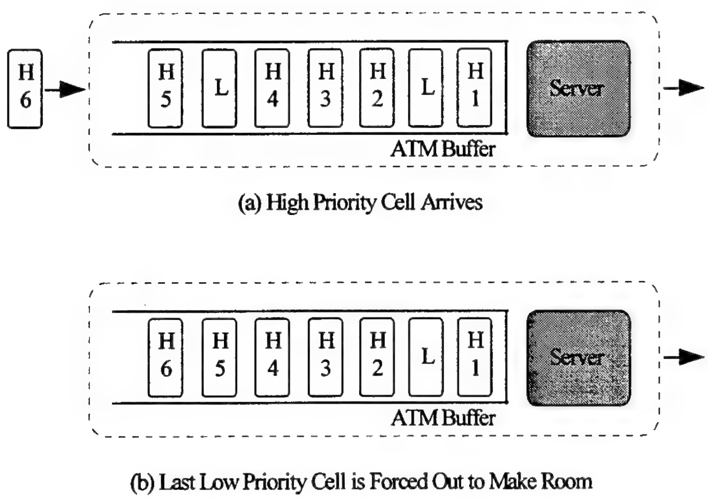


Figure 4: ATM Space Priority Buffer [7]

been no low priority cells in the buffer, the new high priority cell would have been simply discarded. Space priority buffers can also be partitioned so that both high and low priority cells would be accepted to a certain threshold value, and then only high priority cells until the buffer is full [7].

Figure 5 shows an example of a time priority buffer. Part (a) shows the state of the buffer prior to the arrival of two more low priority cells and one priority cell in the next time slot. At the start of the next time slot, the first cell in the buffer proceeds to the server while the high priority cell goes to the front of the buffer ahead of the low priority cells. Any other cell to arrive when the buffer is full will be discarded regardless of its priority. The use of time priority will effectively speed up high priority cells at the expense of slowing down low priority cells. An example would be that high priority real-time applications such as audio and video would proceed as quickly as possible, while low priority cells such as data in which speed is not crucial would experience a longer delay.

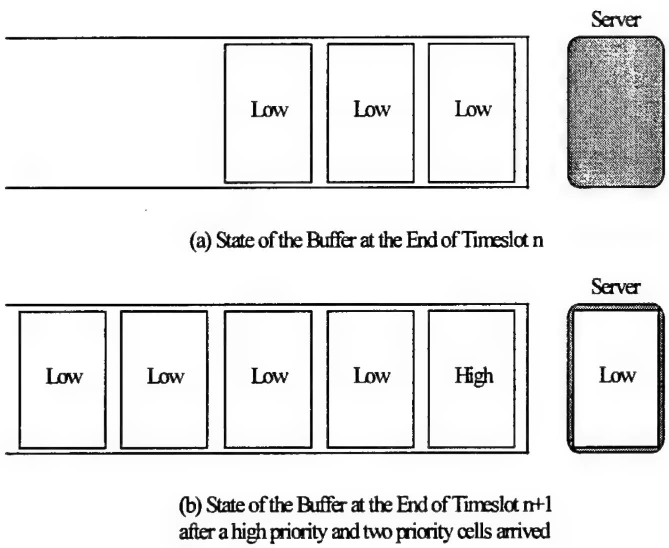


Figure 5: ATM Time Priority Buffer [7]

ATM networks are able to provide a certain QoS based upon the probability that a cell will be lost, the average delay a cell will undergo, how much this delay can vary (also

known as jitter), and the probability the cell will be corrupted. The choice of buffer to use within the ATM network can affect the first three of these parameters, while the quality of the transmission channels and switching equipment can affect the latter. CAC is the process whereby requests for new connections are accepted or denied based upon available resources and the QoS desired. When a connection is admitted, the user and the network accept a type of contract with each other; the network agrees to provide the user with a certain amount of bandwidth at a particular QoS, and the user agrees to send no more than a certain rate of packets into the network. CAC is a very important aspect of the network since it is important to prevent congestion within the network while at the same time trying to minimize the number of calls that are denied connection requests. By using different QoS levels, the network is able to service a greater number of varied users since, while the network may be unable to accept an additional high QoS user, it may be able to accept several low QoS users. The design of the buffers in the ATM network depends on the CAC parameters. The easiest approach is to base the CAC on peak cell rate only [known as deterministic bit-rate (DBR)] which limits the combined peak cell rate of all the VCs through a buffer to less than or equal to the service capacity of the buffer [7]. This approach means that there is normally a large amount of unused bandwidth since it is unlikely that all of the users are operating at their peak cell rate. By adding another parameter to the CAC, the mean cell rate, the network is able to accept traffic greater than the peak cell rate. This approach is called statistical bit-rate (SBR) transfer capability [7] or statistical multiplexing.

UPC is necessary to make sure the user does not violate the contract, but is not trivial to implement for statistical multiplexing. The problem is that although a user may send packets at a rate lower than the agreed upon peak cell rate, the users' packets may have to travel through one or more buffers in the access network before being monitored by the ATM network's UPC. The effect of queueing by the interim network's buffers can cause the packets to arrive in the ATM network at a rate greater than or lower than the agreed upon rate--this is known as cell delay variation (CDV). The leaky bucket algorithm is a common technique employed by UPC to try to take these variations into account.

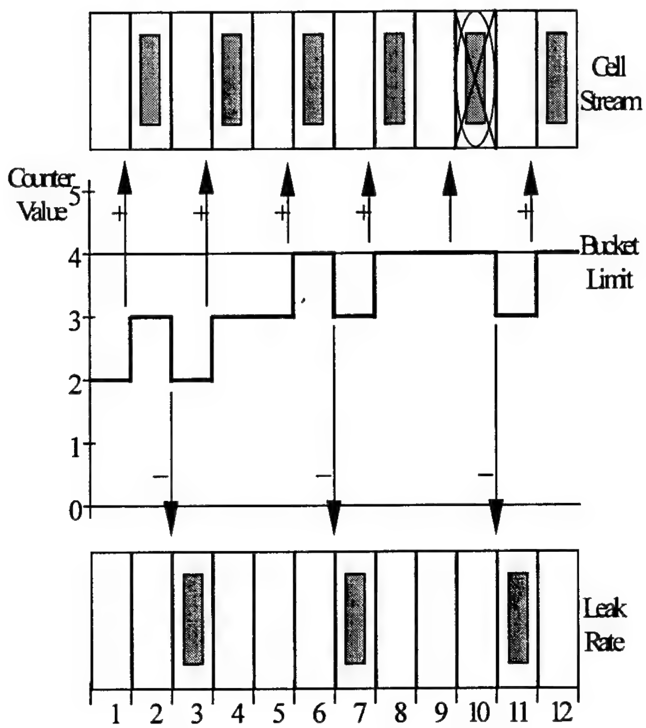


Figure 6: ATM Leaky Bucket [7]

Figure 6 illustrates how the leaky bucket algorithm operates. The UPC increments a counter whenever a cell arrives and then decrements it at a specified leak rate, every four packet slots in this case. If the user sends a burst of cells at a rate that exceeds the leak rate, the bucket will eventually overflow and overflow cells will either be discarded or have their priority changed. Figure 6 shows the user sending a cell in every other slot with the counter at an

initial count of two. The tenth slot is the first cell to be an overflow cell in this case. The leaky bucket is not an actual buffer, it is only an algorithm used by UPC to deal with CDV and other bursts of data [7].

2.1.4. ATM Adaptation Layer

Communications between user applications and networks is commonly described by a protocol stack. The most commonly used description of a protocol stack is called open systems interconnection (OSI), as shown in Table 2. The ATM adaptation layer (AAL) protocol is the protocol layer between the upper network protocol layer and the ATM layer [9].

Both the AAL and the ATM layer can be considered sublayers of the data link layer, with the AAL acting as the interface to transform packets formed by the upper layers into the fixed ATM packet format for use in the ATM layer.

Table 2: OSI Seven-Layer Model [9]

Layer	**Function**
Application (Layer 7)	Support of user functions such as file transfer, transaction processing, etc.
Presentation (Layer 6)	Transfer syntaxes (character coding).
Session (Layer 5)	Coordination services, dialogue, synchronization.
Transport (Layer 4)	Reliable end-end communication.
Network (Layer 3)	Delivery within a single network. End-to-end aspects, such as addressing and internetworking.
Data Link (Layer 2)	Delivery of blocks of data (e.g., cells) between two points; the ATM and the ATM Adaptation Layers are sublayers within the Data Link Layer.
Physical (Layer 1)	Bit transmission.

The ITU-T applied three broad end-to-end (network external) criteria to distinguish four classes of ATM service: Timing requirement between source and destination; Bit rate; Connection mode [9]. Five types of AALs were originally defined to deal with these four

service classes, see Figure 7. Type 2 has not been fully defined yet and Type 5 is a simplified version of Type 3 with lower overhead and better error correction. Types 3 and 4 are very similar with only connection oriented versus connectionless oriented modes being the main difference, so the two types were combined into Type 3/4.

Service / Parameter	Class A	Class B	Class C	Class D
User Application	Voice, Video, Clear Channel	Packet Video	Connection-Oriented Data	Connection-less Oriented Data
Timing (Source-Destination)	Required		Not Required	
Connection Mode	Connection Oriented			Connection-less
Bit Rate	Constant	Variable		
AAL Type	Type 1	Type 2	Type 3 Type 5	Type 4

Figure 7: ATM Service Classes and AAL Types [6], [9]

Constant bit rate (CBR) traffic is traffic generated by Class A customers, variable bit rate (VBR) are the other classes, and available bit rate is also part of Class D. CBR would be like a video conference or audio call, connection oriented VBR would be like X.25 service, connectionless VBR would be similar to a LAN, and ABR would be similar to TCP/IP data. The proper AAL will segment this data, add the Type appropriate control header and trailers, then send the segments to the ATM layer where the ATM headers are applied, and

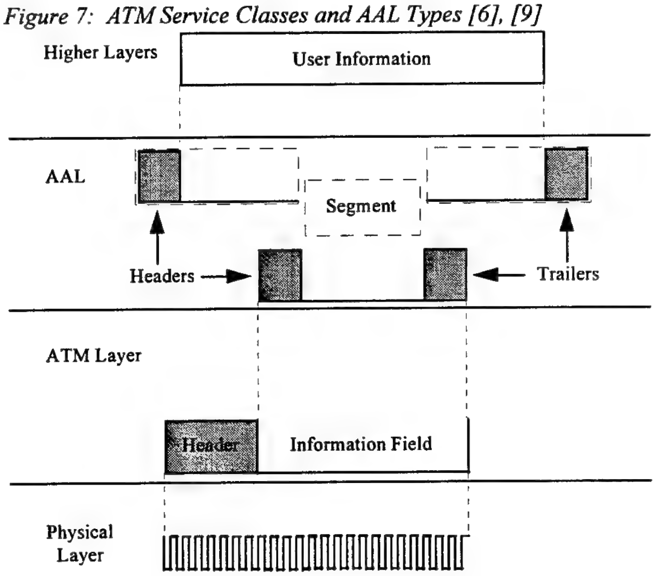


Figure 8: ATM Protocol Layering [7]

the ATM packets are complete as illustrated in Figure 8 [8].

2.1.5. ATM packets

The ATM packet is a fixed packet size of 53 bytes. There are 48 bytes for the information field, which also contains any control bits from the AAL, and a 5 byte header. The header contains the following fields contained in Table 3.

The GFC field is generally not used but is intended for use within a particular network in the user-to-network interface (UNI). It is dropped and the VPI is expanded to include its four bits when the ATM packet is used in the network-to-network interface (NNI).

Table 3: ATM Header Fields [10]

Number of Bits	Field Label	Field Name
4	GFC	General Flow Control
8	VPI	Virtual Path Identifier
16	VCI	Virtual Channel Identifier
3	PT	Payload Type
1	CLP	Cell Loss Priority
8	HEC	Header Error Check

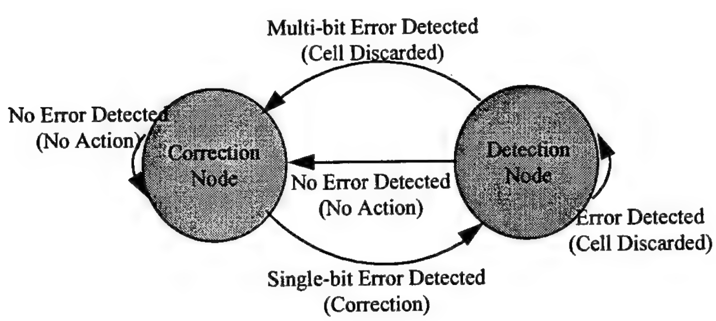


Figure 9: ATM HEC State Diagram [11]

The PT field is used to differentiate user data packets from network operations and maintenance (OAM) packets [6]. The CLP can be set by the user or the UPC to show

a high or low priority cell to affect how it is handled in the buffers during times of congestion.

The HEC field enables the network to detect errors in the header only. The HEC can correct a single one-bit error, but if it detects a multi-bit error the cell is discarded, or if it detects two or more cells in a row with errors, they are all discarded as shown in Figure 9. The HEC algorithm first begins in the correction node and then proceeds as stated. This method was designed for very clean transmission paths as is normally the case with fiber optic physical links, and is not normally adequate for wireless paths.

2.2. The Wireless Network

The medium for wireless networks involves some issues that are different than those for wired networks. Unlike the wired medium, the wireless medium has a fixed amount of frequency bandwidth available which can not be increased by adding another wire. As technology becomes more advanced, this frequency spectrum is becoming more of a scarce commodity. It is therefore imperative that the wireless network utilize this scarce commodity in an efficient manner.

2.2.1. Multiple Access Techniques

In order for a network to be effective, more than one user must be able to access the transmission medium at the same time. It is through the use of a multiple access scheme such as frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), or some variation or combination of these, that multiple users are able to access the network.

2.2.1.1.FDMA

The FDMA technique splits the available frequency spectrum into a number of smaller bandwidth channels. These channels are then assigned to individual users and they then are able to transmit their data within the narrower frequency bandwidth of the channel. Figure 10 shows an example of FDMA with separate frequencies assigned as the uplink and the downlink.

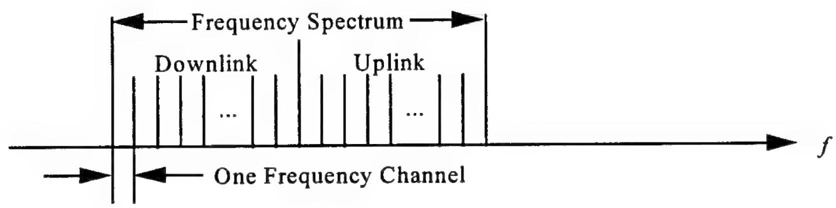


Figure 10: FDMA Example [12]

Advantages of FDMA are that capacity can be increased by decreasing the information bit rate and using efficient digital codes, technological advances are relatively simple, and the system can be configured so that improvements in speech coder bit rate reduction are easily incorporated. Disadvantages are that only modest capacity improvements can be expected since improvements are dependent upon lower signal-to-interference (S/I) ratio, narrowband filter necessary in this case are not yet available in very large-scale integrated (VLSI) circuits, and the maximum bit rate per channel is fixed, small, and therefore is not flexible enough by itself for ATM purposes **[1]**.

2.2.1.2.TDMA

TDMA uses a different approach in that the entire frequency spectrum is utilized. In this case the users are given specific time slots in which they are allowed to transmit

their data. The collection of time slots is called a frame and the frames repeat themselves continuously. Figure 11 shows an example of TDMA.

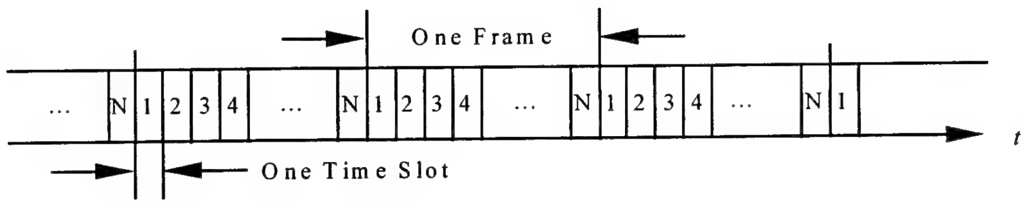


Figure 11: TDMA Example [12]

TDMA offers several advantages: It permits a flexible bit rate, which is important for ATM; It can be integrated into VLSI without narrowband filters; It can offer frame-by-frame monitoring of signal strength/bit error rates to initiate hand-offs; It utilizes bandwidth more efficiently, even though guard times are needed, since frequency guard bands are not needed; It transmits each signal with enough guard time to adjust for problems such as timing inaccuracies, delay spread, propagation delays, and transient responses. Disadvantages of TDMA are that each user transmits over the entire frequency bandwidth during their time slot, which demands high peak power and can shorten battery life; TDMA requires a significant amount of signal processing in order to become synchronized with a time slot [1].

2.2.1.3.CDMA

Each user in CDMA is assigned a unique spectrum spreading sequence that is applied to its data and the resultant signal is spread across the entire frequency bandwidth for the duration of the call. All of the other users are received by each user as being noise or interference. This interference is reduced by the spreading factor or processor gain, after the composite signal is despread [12]. The advantages of CDMA are that it has the

ability to tolerate a fair amount of interfering signals. This means problems of frequency band alignment and adjacent cell interference are minimized. Capacity is improved when a user is not transmitting voice or data thereby allowing CDMA to handle more users [1]. The disadvantages include varying signal strength and the complexity in implementing CDMA. The varying signal strength resultant of the different distances between multiple users and the base station, can overpower a particular user's composite signal.

2.2.2. Duplexing

The channels assigned in these multiple access techniques are all one way channels. Most data communications require a two way or duplex interchange between two users. These two directions are commonly called the uplink (the user to base station) channel and the downlink (the base station to user) channel. FDMA and TDMA normally utilize one of two duplexing techniques, frequency division duplexing (FDD) or time division duplexing (TDD). FDD and CDMA splits the total frequency spectrum into two parts; one used for the uplink channels and the other used for the downlink channels as depicted in Figure 10 for FDMA. TDD splits the TDMA frame in two with one half used for the uplink channels and the other half used for the downlink channels. Either FDMA or TDMA can utilize either FDD or TDD. It is even possible to mix FDMA and TDMA by using TDMA frames on FDMA channels.

2.2.3. Medium Access Control (MAC)

Only one data source at a time can successfully transmit data on a wired medium. Wired MAC is concerned with accomplishing this goal when there is more than one user wanting to use the channel at the same time. On the local network level, contention is

normally handled by carrier sense multiple access with collision detection (CSMA/CD) or token passing. Since it would be impractical for wireless users to have permanently assigned channels, there must be a means in place for a new user to request a channel assignment. Wireless MAC normally supplies a contention based reservation channel for this purpose that is subject to the same restraints as wired MAC. In addition, wireless users are not normally able to hear all the other users in the wireless network due to distances or directional antennas. This further complicates matters since CSMA/CD and token passing would only work in a limited way, if at all, in this type of environment.

The University of Hawaii addressed this contention problem in the 1970s with the development of the ALOHA system to enable a packet radio network to operate between the different Hawaiian islands. A user station would simply transmit its data when it had it regardless of anyone else transmitting at the same time. The base station would broadcast an acknowledgment for any packets it successfully received. If the user station did not hear its message acknowledged, it would retransmit after waiting a random period of time. Thus if packets from two or more stations collided, the base station would not successfully receive any of the conflicting stations and would not send an acknowledgment for any of them. The conflicting stations would then retransmit after a random time delay, until their packets successfully got through. A modification of ALOHA known as slotted ALOHA improves the performance of pure ALOHA by dividing the transmission time into fixed-length time slots where a user station must wait to send its packets until they coincide with the beginning of a slot. This technique has the

effect of improving the maximum utilization of pure ALOHA from 18% to a maximum utilization of 36% [11].

2.3. Dealing with the Wireless Environment

The wireless environment poses unique challenges that are not present within the wired environment. orthogonal frequency division multiplexing (OFDM) may be an efficient way to combat these problems.

2.3.1. Problems in the Environment

Wireless networking uses electromagnetic energy in the form of radio waves to carry user's data. In free space, radio waves travel in straight lines and are reflected off of objects in a similar way as light is reflected off of objects. However, when operating in rural or urban environments, several phenomenon can affect these radio waves. Multipath propagation is one such phenomena that is caused by the superposition of radio waves reflected from surrounding objects. This can cause frequency selective fading leading to deep and frequent reductions in received power and , with mobile users, rapidly changing time variance of received data. Another phenomenon, shadow fading, is caused by large physical objects (like buildings or hills) that interfere with the line of sight between the user and the base station. This also leads to reductions in received power, but varies at a lower rate than multipath fading. The phenomenon of path loss is simply the reduction in received power as the user and the base station become further apart [12]. Doppler shift is a phenomenon present whenever motion is involved. This motion may be the user, the base station, or something in the environment itself and can again affect the timing and the phase of the user's data [1]. Besides affecting the received

signal power, these phenomena can cause co-channel and intersymbol interference as well.

2.3.2. Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is a possible modulation scheme that can be used to combat these problems in the wireless environment. Ayanoglu et al. [5] mentions some of these desirable properties: it simplifies equalization considerably, it has graceful performance degradation, and it has lower complexity because of the absence of equalization. They summarize by recognizing that OFDM is an attractive alternative, but that more research is required before OFDM can be used on a large scale. OFDM utilizes the combining of a number of digitally-modulated carriers into an ensemble in a form similar to spread spectrum utilization, see Figure 12 [13].

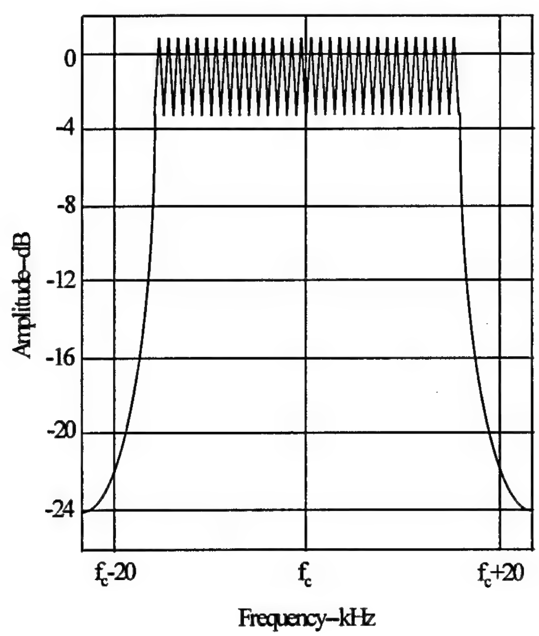


Figure 12: OFDM Signal with 32 Carriers

and 1.25 ms Symbol Length [13]

This technique allows the channel information to be split between the different carriers and at the same time, increase the symbol duration. The total bit rate and bandwidth are constant with respect to a single carrier using the same modulation technique. This decreases the number of symbol errors generated by multi-path propagation and co-channel interference [13]. This reaction to the environmental phenomena results in a more robust access technique with a lower BER that is highly desirable in an ATM network. OFDM therefore looks like a possible candidate for a wireless ATM network.

2.4. Review of Previous Literature

There have been several articles written in the past few years about wireless ATM--some of which have material of interest to this project. Some are examples used in this model and others are alternative approaches.

2.4.1. Raychaudhuri--WATMnet

Raychaudhuri [14] describes a more common approach to a prototype wireless ATM network called WATMnet developed at NEC USA's C&C Research Laboratories. This approach uses a TDMA/TDD frame divided into a TDM downlink made up of control slots for reservation assignment and acknowledgments, a slotted ALOHA uplink for new users to request reservations, and a TDMA uplink with allocated portions dedicated to ABR/UBR, VBR, and CBR (see Figure 13).

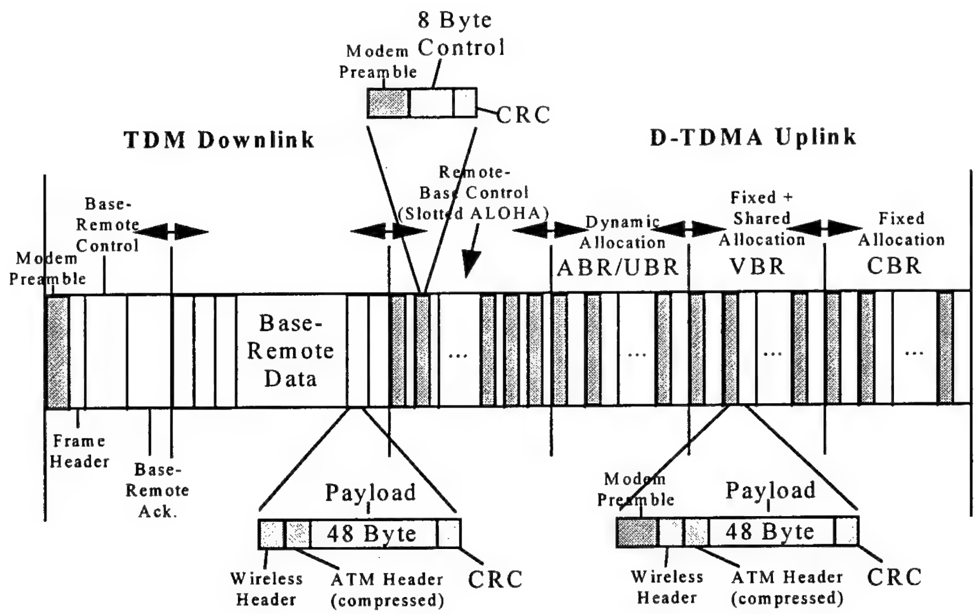


Figure 13: Dynamic TDMA/TDD Control Frame [14]

He describes a protocol whereas ABR is allocated slots on a frame by frame basis, CBR is given fixed periodic slots, and VBR is assigned a combination of the two. He states that this protocol has been shown to yield a throughput of 0.6 to 0.7 with reasonable performance after accounting for control and physical layer overheads. These overheads include extra error correction and detection to account for the fact that the wireless channel has a much higher Bit Error Rate (BER) than the wired medium ATM was originally designed for. They also include extra information needed for the wireless base station to handle hand-off issues and other wireless issues. These extra bytes of information encapsulate the ATM cell, which already includes almost 10% of overhead. These bytes add to the overall overhead thereby diminishing the available information throughput.

2.4.2. Acampora--antenna elements

The majority of the papers available on wireless ATM tend to emphasize the use of TDMA for MAC. There appears to be two main approaches to reservation channel requests, slotted ALOHA and polling. Acampora [12] proposes an interesting approach to solving the problem of time-varying channel impairments. He describes the use of array antennas utilizing a complex weighting multiplier to attenuate and phase shift a branch of the composite signal received at each antenna to diminish the effects of multi-path, noise, and channel interference. This technique makes use of polling to assign TDMA slots to the user. The base station will poll a user station using token passing, as to whether it has data or not. The user station will respond with a short tone to allow the base station to adjust antenna weights, and will then send its data if it has any. If it doesn't have any, the base station will now pass the token to the next station in line. For the base station to send data to the user station, the base station first requests a pilot tone from the user station in order to calculate new antenna weights.

2.4.3. Goodman--PRMA

Goodman [2] describes an interesting contention-based multiple-access scheme known as packet reservation multiple access (PRMA). This scheme uses slotted ALOHA for the entire frequency bandwidth in a mixture of ALOHA and TDMA. A frame of time slots is repeated continuously with user stations monitoring whether a slot has been tagged as available or reserved on the basis of a feedback packet broadcast in the prior frame. If a user succeeds in sending a request in one of the available slots, the base station will inform all users of the new assignment. The user will continue to have exclusive use of the slot until the user fails to send a packet in it. The base station will

then observe the empty slot and inform all users that the slot is now available. Thus bandwidth is only allocated when it is used and not during silent periods.

Chapter 3

3. Approach and Simulation Design

Simulation is the use of a model to represent a system. This representation enables one to measure characteristics and properties of the system. Simulations are classified as one of three types: continuous-time, discrete-time, or discrete-event. Continuous-time and discrete-time simulations are normally described by differential equations or difference equations; whereas discrete event simulation is modeled after systems with countable events. These events typically are discrete and nothing of interest occurs between the events [15]. The Summit County network is an example of users accessing the network in a random probabilistic fashion. This lends itself to discrete-event simulation as a logical approach to modeling the system.

Continuous-time and discrete-time simulations normally consist of a two-step process of simulation. The first step is building an abstract model based upon the real system, and the second step is developing the actual simulation program from the model. Discrete-event simulations have an interim step (see Figure 14) to build a language specific model since discrete-event simulation does not have the same historical development and theoretical background the other types of simulations share [15].

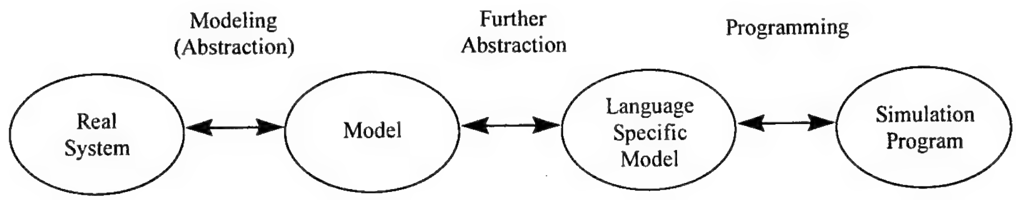


Figure 14: Discrete Event Simulation Modeling Process [15]

The next section of Chapter 3 will describe the intended real system for Summit County while the other sections of Chapter 3 will describe the steps leading to the simulation program itself. Excerpts from the programs are presented in the Appendix while full listings of the program are available in a separate document.

3.1. The Summit County System

The real system used to represent the wireless network applied to Summit County is basically two parts. The first part is a wireless local anchor/tenant network based upon an individual town within Summit County. The second part is a network of the towns of Summit County connected together in a wireless backbone.

3.1.1. The Local Anchor/Tenant Network

Figure 15 shows an example system of five users accessing a local base station in Summit County. The system is assumed to use a combination of OFDM and TDMA as the means to transmit and receive between the user stations and the base station. The user stations will most likely use only small groups of OFDM carriers with directional antennas to transmit on, in order to conserve transmitter power. If the user stations were to transmit across the entire OFDM frequency groups, a fairly substantial amount of power would be required and may not be practical for a smaller, possibly portable, user station. The base station transmits omni-directionally to all of the stations at the same

time. It utilizes time division multiplexing to transmit information to individual stations. This system assumes the users are stationary.

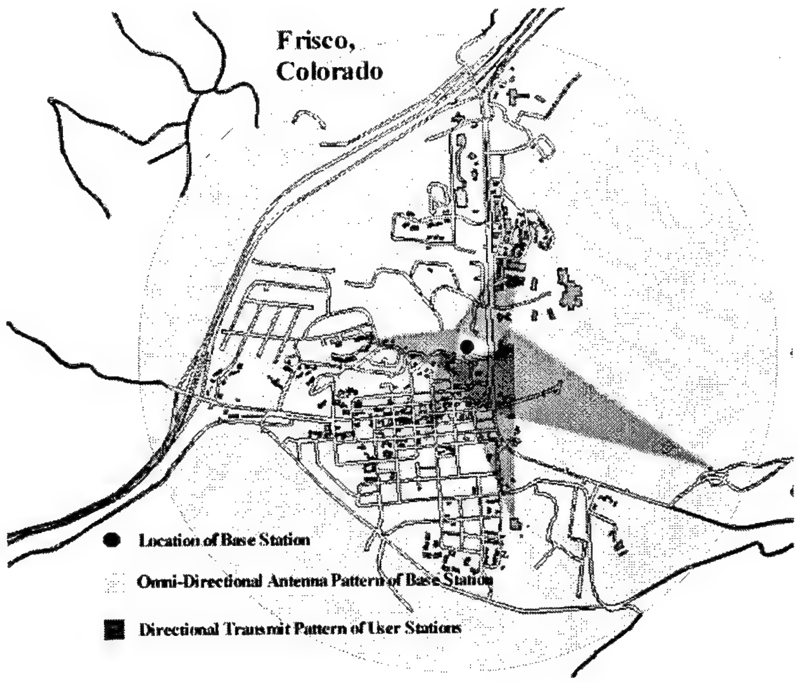


Figure 15: Wireless Local Area Node [16]

3.1.2. The Backbone Network

The backbone network connecting the local nodes of each town (which can consist of more than one anchor/tenant station connected in a cellular fashion if necessary) are also connected via wireless OFDM/TDMA. In this real-system approximation of Summit County, there are four nodes assigned to the towns shown in Figure 16. In addition, the node consisting of the towns of Silverthorne and Dillon is connected to the high speed PSTN via wired trunk lines following Interstate 70. This PSTN access allows users within the Summit County wireless network to connect with

users outside of the network and vice versa, through the Internet, to anywhere in the world.

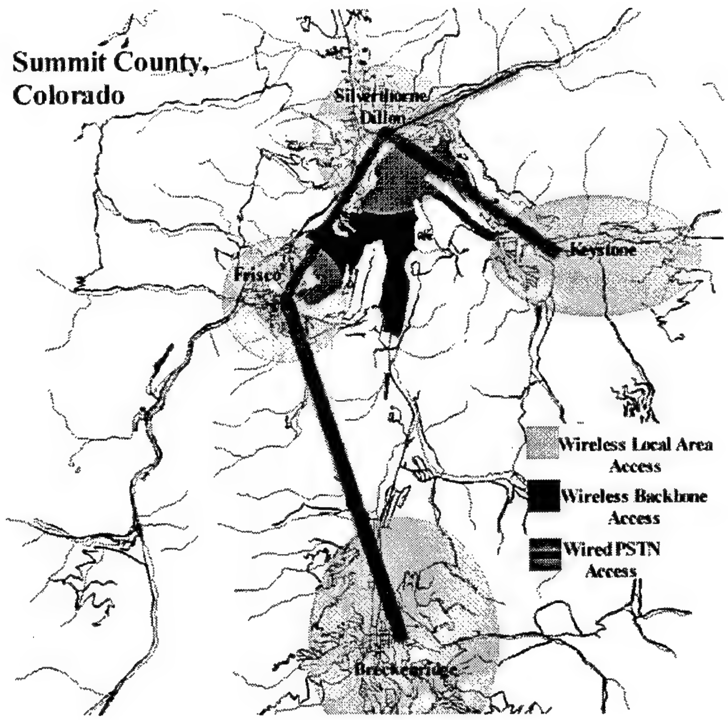


Figure 16: Wireless Backbone/Local Network [16].

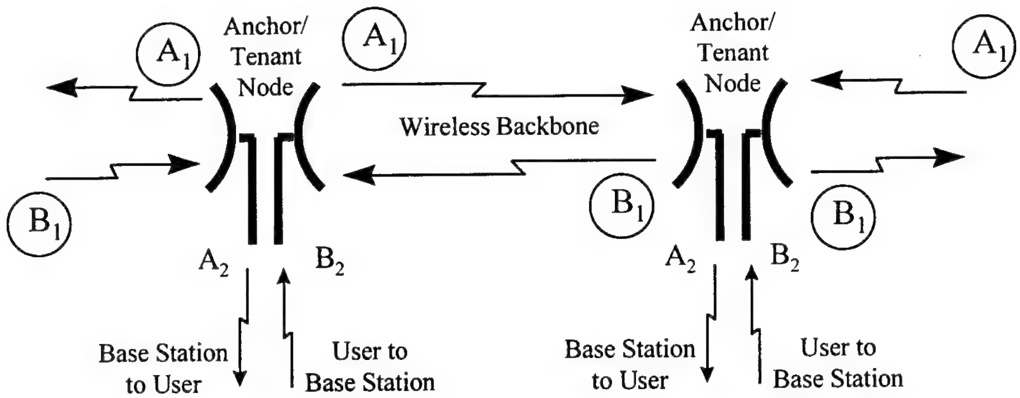
3.2. Design Parameters and Considerations

Certain design parameters and considerations have helped to shape the layout of the model used to produce the simulation programs used in this thesis. Multiple users must be able to access the network at the same time with a variety of different uses. Frequency bandwidth and time of transmission/reception is managed by the ATM protocol with OFDM/TDMA utilization of the frequency spectrum.

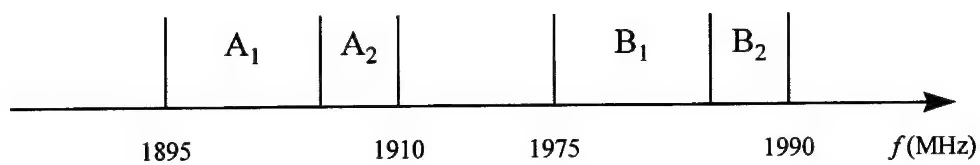
3.2.1. Frequency allocation--Uplinks and Downlinks

The model envisions duplexing the information between the user and the base station, and between the anchor/tenant nodes through the use of separate uplink and downlink frequency bands. There are separate pairs of frequency bands used for the uplink and downlink local areas of the towns themselves, and for the different directions of the links between the towns. These frequency bands correspond to an FCC pair of 15 MHz frequency bands designated Block C for PCS communications. These bands consist of a 1895-1910 MHz PS (Personal Station) transmit band and a 1975-1990 MHz RS (Radio System) transmit band [1]. The network may possibly allocate these bands dynamically as required by the demands on the system, or they may be fixed and operated with a rigid allocation schedule.

Figure 17 (a) shows the frequency bands Figure 17 (b) shows how the network may allocate the frequencies between the wireless backbone and the local users. It may be possible to adjust these bands dynamically as demand increases in some areas and decreases in others. In areas of denser populations, it could be possible to split the A_2 and B_2 frequencies (also known as downlink and uplink frequencies) into "cells" to take advantage of frequency re-use.



b. Possible Utilization Scheme for Wireless Network



a. PCS C-Band Frequency Allocation

Figure 17: Wireless Network Utilization of Frequency Band

3.2.2. The Contention Based Reservation Channel and Dynamic Allocation

Since the network is using the ATM network protocol, it is necessary to be able to dynamically assign channels and bandwidth to users to accommodate their requests and types of traffic. Regardless of the mix of OFDM and TDMA involved, users will need to request the channel connection and the network will need to assign the proper OFDM frequency group and/or TDMA time slot. The users in the local areas will be using directional antennas with antenna coverage only about half the size of the entire cell. This means that a contention based reservation channel utilizing ALOHA would be the

most practical approach since the users can not effectively use collision detection. This model will utilize slotted ALOHA since it is approximately twice as effective in terms of throughput as pure ALOHA.

Despite the degree of OFDM or TDMA used, it is easy to envision that a frame type of synchronization will be used. This frame will coordinate the use and timing of the different OFDM frequency carrier groups and/or TDMA time slots for ATM channels. Raychaudhuri's diagram of the WATM net TDMA superframe depicted in Chapter 2 Figure 13, is a good way to visualize the timing involved for TDMA and could also be applied to OFDM carrier groups in a similar manner. In any case, some type of timing synchronization will be necessary, whether it is inherent in the OFDM symbols or in the header of the TDMA superframe.

3.2.3. ARQ/FEC and OFDM required overheads

The ATM header error detection and single-bit correction described in Chapter 2 is adequate for wired mediums with very low Bit Error Rates (BER). It is inadequate, however, for the much higher BERs of wireless mediums. It will be necessary to apply some additional type of protection such as automatic repeat request for retransmission (ARQ) or forward error correction (FEC). Raychaudhuri described a technique used in the WATM net of compressing the ATM header and adding additional bits in a wireless header for additional error correction and detection in the wireless link [14]. The OFDM symbol also has error detection built into it and will also help to improve the BER for the ATM cells encompassed within. It may be possible to include ARQ for certain types of traffic such as ABR and VBR where sequential delivery and timeliness are not as critical

as for CBR traffic. This all equates to additional overhead to the almost 10% ATM overhead; although, compressing the ATM header as Raychaudhuri suggests could help to offset the additional overhead somewhat.

3.3. Simulation Approach and Assumptions

The model has been split into three pieces in order to help make analysis easier and the simulation runs more timely. The first part is a simulation of the ALOHA reservation channel. Models with pure ALOHA and slotted ALOHA have been developed and compared. The second part is the largest and models connection requests and bandwidth allocation for the entire network on both the local anchor/tenant level and the wireless backbone level. The third part models output buffers in use on the wireless links of the backbone and provides analysis on the actual ATM cell level. Where possible, similar assumptions and approaches are made.

3.3.1. ATM/OFDM conversion

This model will not be concerned with the actual implementation of the OFDM carrier groups into channels. Undoubtedly different approaches can affect efficiency and therefore overall data rate, but this model will assume that the entire bandwidth is available and used efficiently. The model assumes a one-to-one correspondence between a 7700 Hz block rate per 1 MHz frequency bandwidth that increases linearly as the bandwidth increases [17]. It assumes that one ATM cell will be contained in one OFDM block and as the frequency bandwidth is increased, the available OFDM blocks increase linearly. In fact, there is some degradation as frequency bandwidth is increased according to [17], but that is not dealt with in this model in order to show an ideal simplified case.

3.3.2. Data generation

There are assumed to be five types of data for all three parts: A low rate CBR to simulate an audio call; A medium rate CBR to simulate a low quality video conference; A high rate CBR to simulate a high quality video conference; A VBR rate to simulate data transfer; An ABR rate to simulate e-mail or remote monitoring of reservoirs, wells, and other similar traffic types.

Table 4: Network Data Traffic

Type	Data Rate (kbits/sec)	ATM cells/sec (384 bits)	Requests/day per User	Message Length
Low CBR	32	84	2	5 minutes
Med CBR	384	1000	0.5	10 minutes
High CBR	1152	3000	0.1	20 minutes
VBR	192	500	10	100 KBs
ABR	2	6	5	5 KBs

Table 4 shows the assumptions made for this model. It is relatively simple to change these parameters within the program itself for simulations at other specifications. The parameters for the data rates were estimated from the throughput estimates for third generation traffic in **Table 1** of Chapter 1. Note that all data is converted to equivalent ATM cells throughout the model for simplicity in implementation.

3.3.3. Reserved capacity and common capacity

The overall capacity of the local anchor/tenant nodes is separated into portions for both the uplink and the downlink directions. This is necessary to prevent one type of traffic from dominating the network and preventing other types of traffic from accessing the network. First, the overall frequency bandwidth is allocated for the up and down directions, 5 MHz each in this model but this can be easily changed. It is then converted to an available ATM cell rate via the 7700 Hz per MHz formula mentioned earlier. This

overall capacity is then separated into three pools of reservation capacity for high/medium CBR, low CBR, and VBR, and one pool of common capacity to be evenly shared.

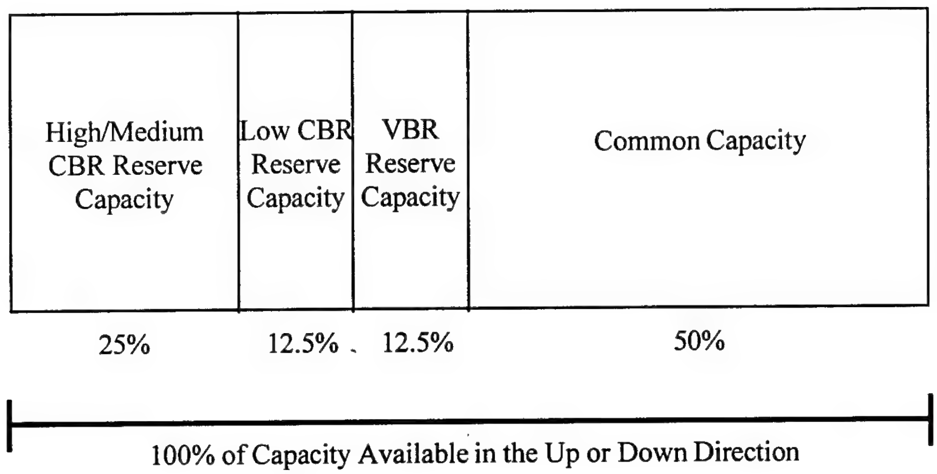


Figure 18: Local Anchor/Tenant Capacity Pools

Figure 18 shows how the capacity is allocated for this model. High and medium CBR is given the greatest amount of reservation capacity since these types of traffic require the greatest amount of capacity. ABR type traffic does not have a reservation pool since this traffic is strictly available bit rate only as its name implies. When a user requests a connection for one of the reservation pool types of traffic, capacity is first checked within that type's reservation pool, and then the common capacity pool. If there is still not enough capacity available, the network will then check the VBR reservation pool, the low CBR reservation pool, and the high/medium CBR reservation pool in that order according to type. If it is still unable to get enough capacity, a flag is set for the appropriate up or down direction, and the opposite direction is checked to see if a flag needs to be set in that direction as well. It is assumed for this model that the caller will

continue to wait until a call is accepted for as long as it takes. The flag ensures that when the network checks a flagged reservation pool for a different type request, it will not be allowed to take the capacity. Eventually, even in a congested network, the waiting caller will get through after one of its own type of traffic calls in progress completes their call and capacity is freed in its reservation pool.

For ABR-type traffic, because of its available bit rate specification, the network will ignore flags when allocating capacity. The network will then pre-empt ABR traffic for non-ABR traffic when the network becomes congested. The network will first pre-empt ABR traffic in the requesting traffic type's reservation pool, then the common capacity pool. It will then pre-empt ABR traffic from other type reservation pools that are not flagged until there is enough capacity for the new request. This process will only proceed if the network determines there is enough capacity available for the new request, between pre-empting the appropriate ABR traffic and the already available capacity.

3.3.4. Buffering and ATM cell delivery

The third part of this model investigates the effect of buffers on ATM cell delay and dropped cells as the network becomes congested. The focus will be on output buffers from the anchor/tenant nodes on the links to the other anchor/tenant nodes. The buffers are treated as strictly FIFO for all types of traffic. The model will supply traffic type ATM cells to the links at the rate and duration of the traffic type for each request. This part will not limit the number of calls on the network and will concentrate on performance as the network becomes loaded at different levels of congestion. The network is driven by a 12 ms timing synchronization frame described earlier. Each link

will have an available amount of ATM cell capacity for each timing frame. If there is available cell capacity on the link for the direction of travel when a cell arrives, it will proceed through the link with no delay. If there is not enough capacity available, the network will then check for available buffer capacity. If there is room, the cell will join the buffer and if there is not, the cell will be discarded. At the beginning of each frame, the buffer is emptied before new cells are processed. It is assumed that the only delays encountered in this network are those of waiting in the buffer.

3.4. Model Layout

The three parts of this model support different aspects of the real Summit County system and are each mini-models in themselves with their own simulation programs. The system presumes the use of timing frames to coordinate channel assignments and this timing frame is in use in each of the models. Each model also uses the same type of data generation to initially create the connection requests or ATM cells. This section of Chapter 3 will show the simulation models and discuss some of the peculiarities of the GPSS programming language.

3.4.1. GPSS fundamentals

GPSS is a discrete-event simulation language. GPSS simulations can be relatively fast depending on the amount of discrete events to be processed, since program execution is driven by events (called transactions) and not by a system clock. GPSS maintains collections of transactions in entities known as chains. Two special chains are the current event chain (CEC) and the future event chain (FEC). Transactions on the CEC have pending control in a FIFO buffer and priority fashion. A transaction which has

control of the program, the top member of the CEC, will proceed through the programs steps (called blocks) until it reaches a block that requires execution in the future. At that point, it will be placed on the FEC again in a FIFO buffer and priority fashion with a marked time to inform GPSS when to place the transaction on the CEC. Control of the program now passes to either the next transaction on the CEC if one exists, or program time jumps ahead to the next marked time on the FEC and the cycle repeats. The order that transactions are processed can be altered by priority assignments so that higher priority transactions can be processed first. This procedure is used in the programs for such processes as pre-empting ABR type traffic and releasing waiting calls by lowering the current transaction's priority and placing it at the back of the CEC. Simple one-to-one comparisons can be accomplished with TEST blocks, but more complicated comparisons and logical processes must use a combination of TEST blocks, arithmetic variables, and Boolean variables. The connection request model makes very extensive use of these variables to test capacity conditions, reservation flag conditions, and waiting calls. Finally, transactions--used to model timing frames, connection requests, and ATM cells—are able to contain parameters that can record whatever desired, such as data rate and message length among others.

3.4.2. Connection Requests and Timing Frame Generation

Each part has five sets of blocks used to generate connection requests representing the five different data types. A new transaction is created in each set of blocks at an exponentially distributed rate dependent upon the request rate of the particular data type. This transaction represents a connection request for that data type and is assigned values

to its parameters representing message type, reservation pool assignment, message length, an uplink data rate, and a downlink data rate. The connection request is then routed to the appropriate area for its particular model.

The timing frame is also generated in a similar set of blocks in each part. It is created at a time interval set by the value of the frame size in milliseconds. The millisecond is the standard unit of time throughout each model so all message lengths and data rates are converted to milliseconds. After the frame is created, it travels through a short series of control blocks used to coordinate actions within the model. It then enters a terminate block and decrements a termination counter. The total running time of the simulation (in number of timing frames) is set in the termination counter at the beginning of the simulation. The simulation terminates when the timing frames decrement the termination counter to zero.

3.4.3. The ALOHA Based Reservation Channel—Model Part 1

Two different models were developed to check the performance of pure ALOHA against slotted ALOHA. For the slotted ALOHA, once a connection request is generated, it is sent to a series of blocks where a random number between 0 and 1 less than the total number of slots is generated. This random number is assigned to one of the request's parameters and the request then checks a user chain called SLOT for any other transactions which may have been assigned the same random number. SLOT is where the requests wait after slot assignment for the next timing frame before they proceed. If there is another request waiting with a matching reservation slot, the transaction in control will set both transactions reservation slot value to a flag value and then join the

chain. Every timing frame interval, a timing frame will be generated which will unlink all of the waiting transactions on the SLOT chain and send them to a test block. The timing frame will then terminate. Each transaction sent to the test block will determine if the flag was set or not. If it is not set, the connection request successfully captured the reservation slot and the transaction is terminated. If there was a conflict the transactions will route from the test block back for reassignment of a new randomized reservation slot number and the process will repeat.

The pure ALOHA model uses a different logic path. This model creates a time space that is the same size as the number of slots would have taken in the slotted ALOHA model. This time slot is used to limit the randomized time conflicting transactions will wait before proceeding. A newly generated request transaction will proceed to a check block where it will check to see if there is a transaction in the user chain SENDING that has not yet completed. If there is, the new transaction will unlink the conflicting transaction sending it back to be reprocessed after waiting a random period of time less than the reference time frame. The new transaction will wait a random period of time also and try to resend. If there is not a transaction still sending, the transaction will assign a finish time to one of its parameters to be checked by following connection request transactions. The transaction will then unlink a transaction in SENDING, if it exists, that has finished and then will join SENDING. Any unlinked finished transaction will then terminate.

3.4.4. The Local Area and Backbone Connection Setup—Model Part 2

Part 2 of the system model is a fairly complex model. Connection setup is provided for the four nodes representing the towns described earlier in this chapter, a fifth node which is a wired connection to the PSTN, and the three wireless links between the nodes. Capacity is tracked and adjusted for both the uplink and downlink of each node, as well as left and right direction capacity for each link. Figure 19 depicts this network setup.

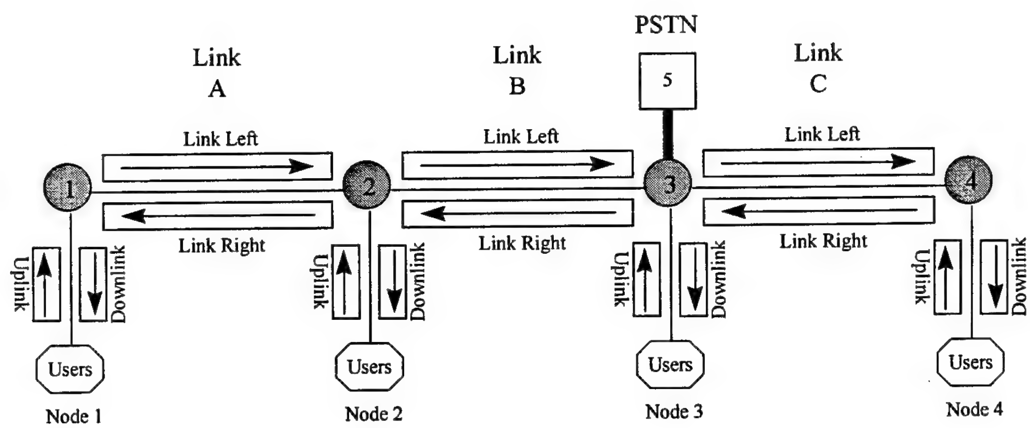


Figure 19: Model Topography for Local Anchor/Tenant and Backbone Data Traffic

The five sets of data generation blocks representing the five data types are repeated four times for the four wireless nodes. When a new connection request is generated at a node, one of the new transaction's parameters is set to record the origination node. The parameter then travels to a set of blocks which determine and record what the destination node is. Traffic originating from node 5, the PSTN, is modeled by changing a small percentage of the traffic requests generated at each of the four wireless nodes to reflect that node as the destination node and node 5 as the

origination node. The resultant transaction then skips the destination determination blocks and travels directly to the path assignment blocks. Each link the transaction must travel to reach its destination and the direction from the original node to the destination node is recorded in the transaction's parameters. These paths are determined as per Table 5.

Table 5: VPI Path Selection

VPI	Original Node	Destination Node	Path
XXXX	1	1	XXXX
1	1	2	Left A
2	2	1	Right A
XXXX	2	2	XXXX
3	1	3 (5)	Left A & Left B
4	3 (5)	1	Right B & Right A
5	2	3 (5)	Left B
6	3 (5)	2	Right B
XXXX	3 (5)	3 (5)	XXXX
7	1	4	Left A & Left B &Left C
8	4	1	Right C & Right B & Right A
9	2	4	Left B & Left C
10	4	2	Right C & Right B
11	3	4	Left C
12	4	3	Right C
XXXX	4	4	XXXX

The transaction travels to a set of control blocks after it has recorded its path parameters. It must wait until the start of a new timing frame before proceeding and once it does, it will set a gate to prevent other transactions from entering the control or capacity allocation blocks until it is done. There are large sets of blocks corresponding to each wireless node that are used to check for available capacity and to take the capacity when directed to do so. The network does not take capacity until it has determined that proper capacity exists at the origination node, the destination node, and each link in between.

The network must determine capacity for the return traffic supporting the call request as well. ABR is the only type traffic in this model which is only one-way traffic, so capacity will be determined in only the origination to destination direction for it. Node 5 is considered to have unlimited capacity in relation to the wireless portions of the network, so capacity determination for it is unnecessary.

The control blocks will determine and send the transaction to the appropriate node blocks for the origination and destination nodes to first check for proper capacity. The simulation uses numerical and Boolean variables to determine whether proper capacity exists as described earlier in the chapter. If there is not enough capacity, the transaction is routed through a set of blocks to set the flags for its type of traffic at the appropriate node. Both nodes will be checked and flags set if necessary before the transaction is sent to join the user chain BUSY. If the network determines there is sufficient capacity at each node in both directions, the transaction will then be routed to a series of blocks to check link capacity, via Boolean variables again. If there is not enough capacity available on one of the links, a flag will be set as long as the transaction is not an ABR type of traffic. Capacity on the links is treated as all common capacity so the flag set for the link is not type specific and will prevent any other transactions from taking the link capacity for that direction. The transaction is then sent to join BUSY. If the transaction passes the link capacity determination, there is enough capacity for it throughout the network. The transaction will take the link capacities first, then be sent back to the control blocks where it will take the node capacities in the same manner as it checked the node capacities. After it has taken all of the capacity it needed, including pre-empting ABR transactions if

necessary, the transaction will reset the gate to allow a new transaction into the control blocks. It will then be placed on the FEC for the duration of its message length parameter.

An ABR type traffic connection request will proceed in a similar fashion except that it will not set any flags if it fails the capacity check and it will not pre-empt other ABR transactions to gain capacity. When it has taken its capacity, it is placed on the user chain ABR instead of the FEC. This is in order for other type transactions to be able to unlink it if necessary to free up capacity. If the transaction is pre-empted, it will go through a series of blocks to give back the capacity it took. All of its parameters will then be reset and a new message length computed to account for the time it was able to transmit. The transaction will then join BUSY.

A successfully completed transaction will go through the same blocks to release its capacity, but instead of resetting its parameters, it will proceed to a series of blocks to check BUSY. The transaction will again utilize Boolean variables to see if there are any transactions on BUSY that first match one of the nodes or links of the freeing transaction, then if there is enough capacity now available for the transaction. If there is, the freed transaction will be sent to take capacity without having to go through the same capacity check it did the first time. The freed transaction will also check with Boolean variables to see if there are other same type transactions waiting in BUSY before resetting the flags that reserve the type reservation pool. The finishing transaction will first check BUSY for type transactions other than ABR. It will then allow new transactions other than ABR to continue. When those are done, it will check BUSY for ABR that has been pre-empted

more than once, ABR that failed its initial capacity check or was pre-empted once, and then new ABR in that order.

This ordering of released transactions is possible through the use of priorities; the different cases of transactions have been assigned differing priorities and as the transaction prepares to process a specific class, it lowers its own priority and places itself back on the CEC. The higher priority transactions will then process through the simulation until they are placed on the FEC at which time the finishing transaction will pick up again and process the next class in a similar manner. After all the classes discussed have been processed, the transaction will be terminated. The timing frame simply resets gates to allow new and finishing requests to process, and it unlinks finished ABR transactions from ABR.

3.4.5. Buffering on the Backbone—Model Sub Part 3

The third part of the system model is concerned only with performance on the wireless backbone. Data generation, destination node, and path determination is accomplished in a similar manner as Part 2. Since this model is concerned with link performance, the destination determination blocks do not allow any transactions to be assigned the same origination and destination nodes and nodes 3 and 5 are not allowed to be assigned to the same transaction for the same reason.

From the path designation blocks, the new transaction will split into two transactions (unless the transaction is one-way ABR); one for the origination to destination data, and the other for the corresponding destination to origination data. These two transactions will proceed to two sets of blocks to generate the transactions

representing individual ATM cells for each direction. These two transactions can be considered master transactions as they will control the generation of the cells. The master transactions will pause on the FEC for a period of time corresponding to the appropriate data rate then will split and send a new transaction or cell to check for passage through the appropriate links. The master transactions will continue to do this for the duration of the message.

The new ATM cell will proceed to a series of blocks to first see if it is able to continue in one of the current timing frame's available slots for the link of interest. If not, it will see if it can get space on the appropriate buffer , or be discarded if the cell fails both tests. If all of the slots have not been used yet, the transaction will proceed with no delay to check any of the other links in its path. If there are no available slots, the network will check for available buffer space and if there is, place the transaction on a user chain called BUFFER. If there is no space available the transaction will be routed directly to the finishing blocks.

The timing frame will reset all of the available transmission slots and buffer slots to their full amounts at the beginning of each frame, and then release all of the waiting cells in BUFFER. They will all proceed in a FIFO fashion through the rest of the links. When they are finished, new cells will be permitted to proceed for the rest of the timing frame. Any cells that are discarded will wait at a gate before they can release the link capacities they took before they were discarded. This gate will be opened by the timing frame at the end of the frame time.

When cells have successfully completed the links they will be sent to a series of finishing blocks to gather statistics and be reassembled. They will proceed to an assemble block were they will be recombined into one cell and wait for the arrival of their master cell. When the master cell arrives, the assembling action will be complete and the one completed cell will terminate. Discarded cells that are part of the same master cell set will also be assembled into the set after they have incremented the appropriate statistics collecting routines.

Chapter 4

4. Results and Analysis

Predictions were made for each simulation model and data was collected to support the predictions. Part 2 was by far the most complex of the simulations and a considerable amount of time was spent on this Part. Overall performance closely followed what was expected. This leads to the conclusion that the three model parts generally reflect the expected real system of the Summit County wireless network.

4.1. Reservation Channel--Slotted ALOHA vs Pure ALOHA

Simulation runs were conducted for both simulations to both check the performance of slotted ALOHA and pure ALOHA and to gain familiarity and confidence with GPSS. In general, the results mirror the expected improved performance of slotted ALOHA over pure ALOHA.

4.1.1. Theoretical results

The maximum capacity is:

$C_{Max} = 1/\tau$ in packets/second.

The carried load is:

$C = C_{Max} \cdot \lambda \cdot \tau \cdot e^{-2\lambda\tau}$ in packets/second.

The average delay between retransmitted packets is:

$R = 1 + a + 2 \cdot \alpha + \delta$ in packet lengths.

The average delay is:

$$D = 1 + \left(\frac{\lambda}{C} - 1\right) \cdot R + \alpha \quad \text{in packet lengths.}$$

λ is the offered load in packets/second given by:

Number users $\times$ (Hi CBR rate + Med CBR rate + Low CBR rate + VBR rate + ABR rate).

τ is the packet length in ms given by the request size/channel rate.

a is the acknowledgment packet length and is assumed to be 0 for this model.

δ is the average packet retransmission delay and is assumed to be equal to the number of reservation slots.

α is the propagation delay and is also assumed to be 0 for this model **[1]**.

The numbers for the carried load were converted to total carried load for the time of the simulation run to be comparable to the results from the simulation. Also, the time for the average delay was adjusted by subtracting the packet transmission time since the simulation did not include the time of the final successful transmission. Table 6 through Table 9 reflect the predicted results for the simulation runs.

Table 6: Predicted 2 Hour Run for Pure ALOHA

Pure ALOHA: Equivalent Reserve Slots = 5, Hours =2			
# of Users	Offered Load (pkts/s)	Carried Load (pkts)	Average Delay (ms)
100	0.02037037	146.6590185	0.000400508
1000	0.203703704	1465.902027	0.004006022
5000	1.018518519	7314.237252	0.020051018
10000	2.037037037	14590.38179	0.040154386
15000	3.055555556	21828.58242	0.060310239
20000	4.074074074	29028.9874	0.080518716
25000	5.092592593	36191.74449	0.100779953
50000	10.18518519	71445.94742	0.20288238
75000	15.27777778	105780.8239	0.306324635
100000	20.37037037	139214.2746	0.411124299

Table 7: Predicted 5 Hour Run for Pure ALOHA

Pure ALOHA: Equivalent Reserve Slots = 5, Hours =5			
# of Users	Offered Load (pkts/s)	Carried Load (pkts)	Average Delay (ms)
100	0.02037037	366.6475462	0.000400508
1000	0.203703704	3664.755066	0.004006022
5000	1.018518519	18285.59313	0.020051018
10000	2.037037037	36475.95449	0.040154386
15000	3.055555556	54571.45605	0.060310239
20000	4.074074074	72572.46849	0.080518716
25000	5.092592593	90479.36123	0.100779953
50000	10.18518519	178614.8685	0.20288238
75000	15.27777778	264452.0598	0.306324635
100000	20.37037037	348035.6865	0.411124299

Table 8: Predicted 2 Hour Run for Slotted ALOHA

Slotted ALOHA: Reserve Slots = 5, Hours =2			
# of Users	Offered Load (pkts/s)	Carried Load (pkts)	Average Delay (ms)
100	0.02037037	146.6628425	0.000200251
1000	0.203703704	1466.284297	0.00200275
5000	1.018518519	7323.779069	0.010018974
10000	2.037037037	14628.4745	0.020051018
15000	3.055555556	21914.1236	0.03009615
20000	4.074074074	29180.76359	0.040154386
25000	5.092592593	36428.43163	0.050225743
50000	10.18518519	72383.48898	0.100779953
75000	15.27777778	107869.7855	0.151664778
100000	20.37037037	142891.8948	0.20288238

Table 9: Predicted 5 Hour Run for Slotted ALOHA

Slotted ALOHA: Reserve Slots = 5, Hours =5			
# of Users	Offered Load (pkts/s)	Carried Load (pkts)	Average Delay (ms)
100	0.02037037	366.6571063	0.000200251
1000	0.203703704	3665.710742	0.00200275
5000	1.018518519	18309.44767	0.010018974
10000	2.037037037	36571.18626	0.020051018
15000	3.055555556	54785.309	0.03009615
20000	4.074074074	72951.90897	0.040154386
25000	5.092592593	91071.07909	0.050225743
50000	10.18518519	180958.7225	0.100779953
75000	15.27777778	269674.4638	0.151664778
100000	20.37037037	357229.7371	0.20288238

4.1.2. Simulation results

Table 10: 2 Hour Pure ALOHA Results (Delay in ms)

Pure Aloha Results										
The Equivalent of 5 Reservation Slots:										
# Users	Init Hrs	Run	Ttl Pkts	Avg Dly	NoCollisions	1 Collision	Dly	Multiples	Dly	Maximum Delay
100	1	2	157	0	157	0	0	0	0	0
1000	1	2	1482	0	1482	0	0	0	0	0
5000	1	2	7224	0.01	7214	6	4.07	4	6.83	11.37
10000	1	2	14598	0.03	14511	58	3.21	29	9.19	16.87
15000	1	2	22065	0.03	21903	116	3.35	46	8.17	19.01
20000	1	2	29321	0.06	29020	184	3.55	117	10.67	33.81
25000	1	2	36776	0.08	36288	301	3.53	187	9.86	27.29
50000	1	2	73050	0.16	71030	1215	3.49	805	9.59	31.9
75000	1	2	109825	0.23	105529	2603	3.48	1693	9.72	40.89
100000	1	2	146849	0.32	139196	4576	3.5	3077	10.03	55.32

Table 11: 5 Hour Pure ALOHA Results (Delay in ms)

Pure Aloha Results										
The Equivalent of 5 Reservation Slots:										
# Users	Init Hrs	Run	Ttl Pkts	Avg Dly	NoCollisions	1 Collision	Dly	Multiples	Dly	Maximum Delay
100	1	5	370	0	370	0	0	0	0	0
1000	1	5	3639	0	3639	0	0	0	0	0
5000	1	5	18402	0.01	18350	34	3.78	18	8.17	14.92
10000	1	5	36677	0.03	36469	130	3.45	78	7.74	15.6
15000	1	5	55266	0.05	54832	257	3.4	177	10.26	29.5
20000	1	5	73277	0.06	72527	441	3.51	309	9.01	31.37
25000	1	5	91547	0.07	90375	711	3.51	461	9.16	29.09
50000	1	5	184478	0.15	179713	2862	3.53	1903	9.32	35.58
75000	1	5	275333	0.23	264455	6618	3.52	4260	9.48	44.22
100000	1	5	367104	0.33	347447	11595	3.5	8062	9.9	61.57

Table 12: 2 Hour Slotted ALOHA Results (Delay in ms)

Slotted Aloha Results										
The Equivalent of 5 Reservation Slots:										
# Users	Init Hrs	Run	Ttl Pkts	Avg Dly	NoCollisions	1 Collision	Dly	Multiples	Dly	Maximum Delay
100	1	2	148	0	148	0	0	0	0	0
1000	1	2	1484	0	1484	0	0	0	0	0
5000	1	2	7284	0.01	7266	12	3.49	6	10	12.35
10000	1	2	14550	0.01	14512	28	3.3	10	10.75	18.22
15000	1	2	21966	0.02	21882	58	3.55	26	10.34	17.11
20000	1	2	29440	0.02	29287	136	3.26	17	10.89	16.17
25000	1	2	36865	0.03	36636	195	3	34	13.49	25.21
50000	1	2	72954	0.07	71960	791	3.29	203	11.46	25.28
75000	1	2	109893	0.1	107727	1711	3.29	455	11.26	38.36
100000	1	2	147104	0.14	143160	3075	3.23	869	11.53	36.09

Table 13: 5 Hour Slotted ALOHA Results (Delay in ms)

Slotted Aloha Results										
The Equivalent of 5 Reservation Slots:										
# Users	Init Hrs	Run	Ttl Pkts	Avg Dly	NoCollisions	1 Collision	Dly	Multiples	Dly	Maximum Delay
100	1	5	367	0	367	0	0	0	0	0
1000	1	5	3621	0	3621	0	0	0	0	0
5000	1	5	18506	0.01	18474	28	2.8	4	8.08	8.96
10000	1	5	36691	0.01	36615	50	3.08	26	11.93	25.43
15000	1	5	55292	0.02	55076	172	3.34	44	11.05	19.17
20000	1	5	73314	0.03	72939	297	3.35	78	10.84	24.63
25000	1	5	91882	0.03	91312	433	3.13	137	11.72	25.38
50000	1	5	184623	0.07	182121	1971	3.12	531	11.13	31.61
75000	1	5	275702	0.09	270471	4081	3.16	1150	11.4	35.53
100000	1	5	366732	0.13	357214	7444	3.2	2074	11.17	47.51

As predicted, the average delays are approximately twice for the pure ALOHA runs than the slotted ALOHA runs. In addition, the measured average delays are very close to the predicted delays in each case. The small delays, even at 100,000 users, indicate that ALOHA is quite adequate as a technique for a contention based reservation channel, and this accomplished with as few as five slots. This leads to the conclusion that the reservation channel will require very little of the overall bandwidth—simulations for

the other parts of the model can therefore disregard the impact of the reservation channel with little effect on the results. Although the carried load increases for the jump from 2 hours to 5 hours, the predicted average delays do not. This indicates the system is not operating near capacity. Results of runs with operation near capacity would be interesting, but was not completed in this case since the main result of minimal bandwidth required is verified.

4.2. Connection Admission Control

As stated earlier, this part of the simulation is by far the most complicated. The parameters used for the data generation are somewhat arbitrary, but can be easily changed to reflect particular requirements by traffic type, node,and link. For this simulation, the values used are the ones presented in Chapter 3 and are the same for each node. The model assumes 5 MHz frequency bandwidth available for the uplink and 5 MHz available for the downlink for each node. It also assumes 10 MHz available for the left entry of each link and 10 MHz available for the right entry of each link. This simulation will set up connection requests and measure how many requests must wait and for how long.

4.2.1. Theoretical results

Predicting how varying the number of users at the nodes affects the capacity utilized in the system is perhaps the most straight-forward way to predict performance in the network. As the capacity utilized approaches 100% utilization, one would expect the number of calls forced to wait for a connection to increase and the waiting time to approach infinity.

Each node will create a number of connection requests to a user at one of the other three wireless nodes, to a user within the same node, or to a user outside of the network via the PSTN (Node 5). Therefore each node will have outgoing requests for a connection as well as incoming requests for a connection. The traffic utilizing the uplink traffic capacity will be made up of outgoing request, outgoing data and incoming request, outgoing data. In a similar fashion, the downlink traffic capacity will be made up of outgoing request, incoming data and incoming request, incoming data. Figure 20 shows how the data generation of all the nodes affects the capacity requirements of one node.

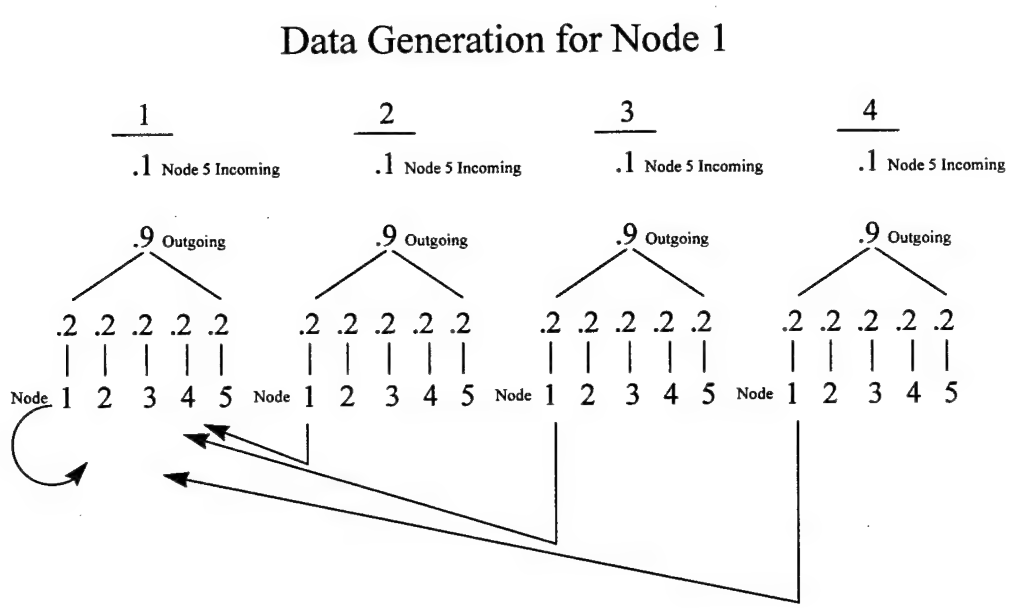


Figure 20: Traffic Routing Effects on Node 1

To compute the capacity levels of the node, the data rates of each type of traffic per user is converted to cells/day. The total capable bandwidth of the uplink and downlink are also converted to cells/day. Notice that 0.9 of the generated traffic within

the node is applied to outgoing requests and 0.1 of the traffic is converted to incoming requests from Node 5. The traffic per user is then:

$.9 \times \text{data generated} + .1 \times \text{data generated} + 4 \times (.9 \times .2) \times \text{data generated}$. Table 14 to Table 16 shows expected figures for this simulation. Results may vary somewhat from these figures, but since the arrivals are exponentially distributed, they should be close in the long run.

Table 14: Cells/day Local Node Data Generation

Outgoing	msg/day	min/msg	sec/min	cells/sec	cells/msg	% uplink	%dwnlink	cells/day uplink	cells/day dwnlink
Low CBR	2	5	60	84		100	100	50400	50400
Med CBR	0.5	10	60	1000		100	100	300000	300000
Hi CBR	0.1	20	60	3000		100	100	360000	360000
VBR	10				261	10	100	261	2610
ABR	5				13	100	0	65	0
Total								710726	713010

Incoming	msg/day	min/msg	sec/min	cells/sec	cells/msg	% uplink	%dwnlink	cells/day uplink	cells/day dwnlink
Low CBR	2	5	60	84		100	100	50400	50400
Med CBR	0.5	10	60	1000		100	100	300000	300000
Hi CBR	0.1	20	60	3000		100	100	360000	360000
VBR	10				261	100	10	2610	261
ABR	5				13	0	100	0	65
Total								713010	710726

Table 15: Local Node Total Capacity

	MHz Up	MHz Dwn	cells/sec/MHz	sec/day	cells/day
uplink	5		7700	86400	3.326E+09
Downlink		5	7700	86400	3.326E+09

Table 16: Number of Users to Percent Capacity

% Capacity	10	20	30	40	50	60	70	80	90	100
Users Up	271.6933	543.3866	815.0799594	1086.773	1358.4666	1630.16	1901.853	2173.546558	2445.239878	2716.933
Users Dwn	271.6528	543.3056	814.9583335	1086.611	1358.2639	1629.917	1901.569	2173.222223	2444.875001	2716.528

Besides the capacity used from the local anchor/tenant nodes, there is also capacity utilized on the wireless backbone. This backbone is modeled as three links and again the capacity is designated as Left Link or Right Link to describe the direction from node to node the particular data is traveling. Figure 20 shows how connections originating from the various nodes impacts the links between the nodes.

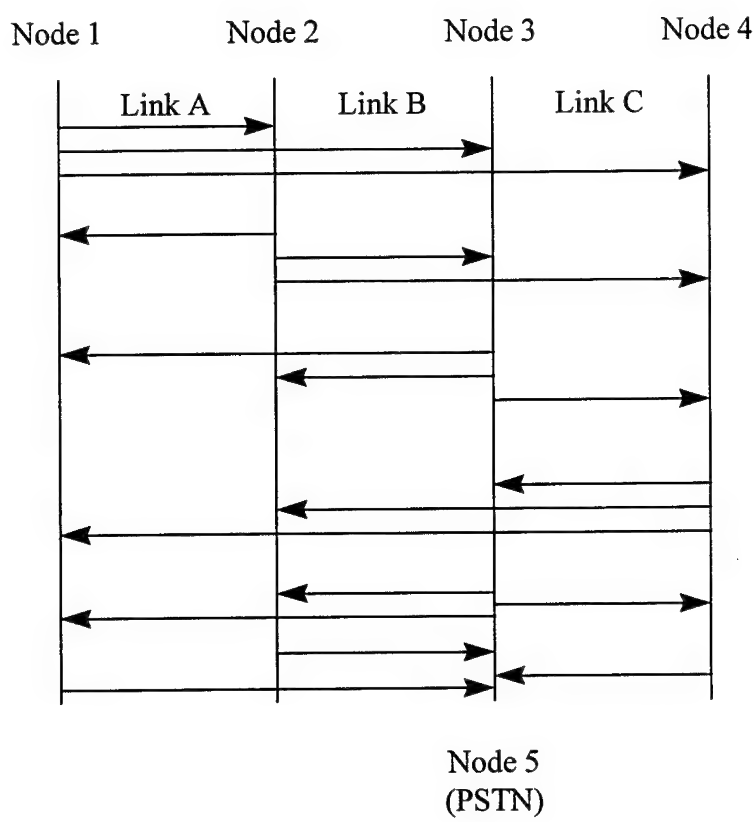


Figure 21: Traffic Affects on Link Capacity

The capacity is again calculated as functions of outgoing connections and incoming connections. The cells/day per user for Link A are:

$$\text{Left Link A} = (4\times.18\text{Outgoing Uplink}+.10\text{Incoming Uplink} + 3\times.18\text{Incoming Uplink})$$

$$\text{Right Link A} = (4\times.18\text{Outgoing Downlink}+.10\text{Incoming Downlink} + 3\times.18\text{Incoming Downlink})$$

The capacity for the number of users is again the total link cells/day divided by the cells/day per user. Table 17 to Table 19 show the link capacity calculations for each link.

Table 17: Total Cells/Day Available per Link

	MHz Left	MHz Right	cells/sec/MHz	sec/day	cells/day
Left Link	10		7700	86400	6652800000
Right Link		10	7700	86400	6652800000

Table 18: Cells/Day Utilized on each Link per User

cells/day/user	Left	Right
Link A	968049.12	968231.84
Link B	1423553.28	1423918.7
Link C	968231.84	968049.12

Table 19: Number of Users per Link Capacity

Link A

% Capacity	40	50	60	70	80	90	100
Left Link	2748.9514	3436.1893	4123.427125	4810.665	5497.90283	6185.140688	6872.37854
Right Link	2748.4326	3435.5408	4122.648972	4809.757	5496.8653	6183.973458	6871.08162

Link B

% Capacity	10	20	30	40	50	60	70	80	90	100
Left Link	467.33762	934.67524	1402.012856	1869.35	2336.68809	2804.025712	3271.36333	3738.7009	4206.039	4673.376
Right Link	467.21768	934.43536	1401.653038	1868.871	2336.0884	2803.306076	3270.52376	3737.7414	4204.959	4672.177

Link C

% Capacity	40	50	60	70	80	90	100
Left Link	2748.4326	3435.5408	4122.648972	4809.757	5496.8653	6183.973458	6871.08162
Right Link	2748.9514	3436.1893	4123.427125	4810.665	5497.90283	6185.140688	6872.37854

It can be observed that Link B is obviously the critical link; however by comparing the number of users per link capacity for Link B and the number of users per node capacity, Link B still has greater capacity than the nodes. These conclusions are good for the long run, but for a short interval of time the exponential nature of the traffic requests and data rate can easily cause bottlenecks on the link or on the node.

4.2.2. Simulation results

Data runs were completed for 1000 users, 2000 users, 3000 users, 4000 users, 5000 users and 10,000 users. Although many statistics were gathered for these runs, the only statistics shown here are for the number of traffic type connection requests generated and the number of these request that had to wait before being connected. The results are tabulated below:

Table 20: Total Network--1000 Users

Users = 1000	Node 1	Node 2	Node 3	Node 4	Node 5
Low CBR	841	905	918	915	386
Med CBR	227	209	221	230	125
Hi CBR	49	44	46	44	32
VBR	4478	4407	4434	4454	2033
ABR	2291	2236	2363	2259	998
Total for Node	7886	7801	7982	7902	3574
Busy Low CBR	2				
Busy Med CBR	2				
Busy Hi CBR	1				
Busy VBR	14				
Busy ABR	2				
Total for Node	21				
Total Attempted	35145				
Total Busy	21				

Table 21: Total Network--2000 Users

Users = 2000	Node 1	Node 2	Node 3	Node 4	Node 5
Low CBR	1741	1831	1823	1838	842
Med CBR	482	460	455	481	218
Hi CBR	87	90	109	110	48
VBR	8974	9027	9051	8948	4043
ABR	4543	4484	4567	4471	2038
Total for Node	15827	15892	16005	15848	7189
Busy Low CBR	108	158	154	265	
Busy Med CBR	106	180	186	280	
Busy Hi CBR	45	64	50	94	
Busy VBR	1346	2116	2149	3079	
Busy ABR	135	177	157	259	
Total for Node	1740	2695	2696	3977	
Total Attempted	70761				
Total Busy	11108				

Table 22: Total Network--3000 Users

Users = 3000	Node 1	Node 2	Node 3	Node 4	Node 5
Low CBR	2670	2742	2741	2731	1230
Med CBR	714	690	701	719	290
Hi CBR	169	149	160	178	60
VBR	13489	13583	13633	13396	5924
ABR	6889	6745	6762	6820	2994
Total for Node	23931	23909	23997	23844	10498
Busy Low CBR	1018	1006	918	1027	
Busy Med CBR	932	909	833	932	
Busy Hi CBR	267	253	253	280	
Busy VBR	10141	9955	9369	10621	
Busy ABR	1270	1208	1188	1287	
Total for Node	13628	13331	12561	14147	
Total Attempted	106179				
Total Busy	53667				

Table 23: Total Network--4000 Users

Users = 4000	Node 1	Node 2	Node 3	Node 4	Node 5
Low CBR	3561	3669	3661	3626	1617
Med CBR	938	889	914	967	417
Hi CBR	245	230	226	249	92
VBR	17861	17964	18087	17982	7921
ABR	9206	9058	8924	9193	3905
Total for Node	31811	31810	31812	32017	13952
Busy Low CBR	1744	1590	1662	1670	
Busy Med CBR	1416	1309	1325	1434	
Busy Hi CBR	399	397	391	430	
Busy VBR	16025	15497	14702	16357	
Busy ABR	2364	2003	2275	2305	
Total for Node	21948	20796	20355	22196	
Total Attempted	141402				
Total Busy	85295				

Table 24: Total Network--5000 Users

Users = 5000	Node 1	Node 2	Node 3	Node 4	Node 5
Low CBR	4482	4601	4536	4557	2054
Med CBR	1204	1160	1217	1235	528
Hi CBR	335	305	306	335	130
VBR	22529	22554	22683	22481	9986
ABR	11613	11380	11394	11586	9910
Total for Node	40163	40000	40136	40194	22608
Busy Low CBR	2573	2552	2824	2783	
Busy Med CBR	1907	1883	1960	1957	
Busy Hi CBR	544	530	545	588	
Busy VBR	21758	20632	20673	22244	
Busy ABR	2755	2626	2661	2508	
Total for Node	29537	28223	28663	30080	
Total Attempted	183101				
Total Busy	116503				

Table 25: Total Network--10,000 Users

Users = 10000	Node 1	Node 2	Node 3	Node 4	Node 5
Low CBR	9131	9069	9024	9056	4016
Med CBR	2922	2830	2974	2941	1031
Hi CBR	682	679	641	675	303
VBR	45125	45060	45197	45110	2014
ABR	23428	23655	23430	23126	9922
Total for Node	81288	81293	81266	80908	17286
Busy Low CBR	7467	7371	7528	7525	
Busy Med CBR	4859	4778	5003	4919	
Busy Hi CBR	1133	1180	1154	1174	
Busy VBR	49554	49024	50130	48600	
Busy ABR	9008	9802	10240	9614	
Total for Node	72021	72155	74055	71832	
Total Attempted	342041				
Total Busy	290063				

One can observe that the program did a consistent job of distributing the amount of requests as one would expect with an exponential distribution. By referring to Figure 22, it is apparent that the number of calls waiting began to increase and follow the calls

attempted around the 2000 users level. This level equates to around the 75% utilization rate from Table 16. The reason Queue performance begins degrading prior to 100% is due to the fact that connections do not always arrive as predicted and may actually arrive in "clumps" having the effect of decreasing the overall performance. It appears that this simulation model mirrors that behavior and as the number of users surpasses the 100% utilization level, the number of calls waiting converges upon the number of calls attempted as one would expect.

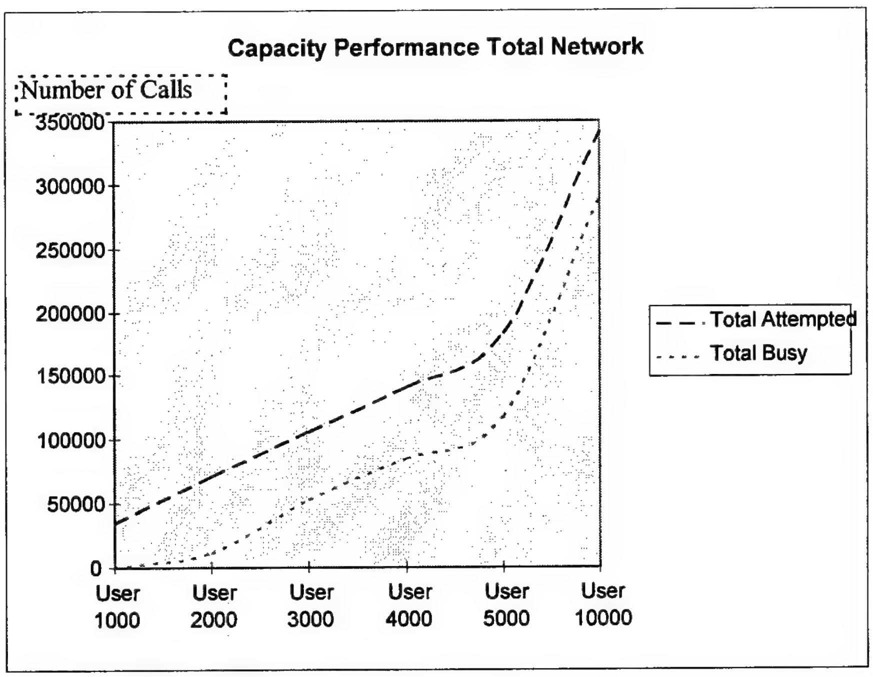


Figure 22: Comparison of Calls Attempted and Calls Waited

Another interesting statistic measured is the number of ABR messages per node and the number of times they have been pre-empted by a higher priority message. It would be expected that the number of messages that are bumped, would increase as the

number of users increases. The following tables show the ABR results for the same simulation runs conducted above.

Table 26: Part 2 ABR Analysis--1000 Users

1000	Node 1	Node 2	Node 3	Node 4	Node 5	
Bumped 0	2289	2235	2363	2259	998	
Bumped 1						
Bumped 2						
Bumped 3						
Bumped 4						
Bumped 5						
Bumped 6						
Bumped 7						
Bumped 8						
Bumped 9						
Overflow						Total
Total Free	2289	2235	2363	2259	998	10144
Total Bumped	0	0	0	0	0	0
					Percent	0%

Table 27: Part 2 ABR Analysis--2000 Users

2000	Node 1	Node 2	Node 3	Node 4	Node 5	
Bumped 0	4465	4428	4506	4396	2038	
Bumped 1	4	4	2	8		
Bumped 2	1	1				
Bumped 3						
Bumped 4						
Bumped 5						
Bumped 6						
Bumped 7						
Bumped 8						
Bumped 9						
Overflow						Total
Total Free	4465	4428	4506	4396	2038	19833
Total Bumped	5	5	2	8	0	20
					Percent	0%

Table 28: Part 2 ABR Analysis--3000 Users

3000	Node 1	Node 2	Node 3	Node 4	Node 5	
Bumped 0	6327	6206	6246	6259	2954	
Bumped 1	109	129	119	104	33	
Bumped 2	25	25	33	36	5	
Bumped 3	12	11	8	4	2	
Bumped 4	3	0	1	3		
Bumped 5		2	1			
Bumped 6		2				
Bumped 7						
Bumped 8						
Bumped 9						
Overflow						Total
Total Free	6327	6206	6246	6259	2954	27992
Total Bumped	149	169	162	147	40	667
					Percent	2%

Table 29: Part 2 ABR Analysis--4000 Users

4000	Node 1	Node 2	Node 3	Node 4	Node 5	
Bumped 0	8186	8159	7926	8146	3784	
Bumped 1	276	269	284	267	79	
Bumped 2	62	69	75	75	30	
Bumped 3	21	25	30	22	3	
Bumped 4	15	10	11	12	3	
Bumped 5	1	4	4	3	3	
Bumped 6	0	0	3	3	2	
Bumped 7	2	1	1			
Bumped 8		1				
Bumped 9						
Overflow						Total
Total Free	8186	8159	7926	8146	3784	36201
Total Bumped	377	379	408	382	120	1666
					Percent	5%

Table 30: Part 2 ABR Analysis--5000 Users

5000	Node 1	Node 2	Node 3	Node 4	Node 5	
Bumped 0	10455	10354	10263	10465	4823	
Bumped 1	224	221	213	204	70	
Bumped 2	52	48	42	39	13	
Bumped 3	19	13	10	14	4	
Bumped 4	5	5	7	4		
Bumped 5	3	2	1			
Bumped 6						
Bumped 7						
Bumped 8						
Bumped 9						
Overflow						Total
Total Free	10455	10354	10263	10465	4823	46360
Total Bumped	303	289	273	261	87	1213
					Percent	3%

Table 31: Part 2 ABR Analysis--10,000 Users

10000	Node 1	Node 2	Node 3	Node 4	Node 5	
Bumped 0	19353	19211	19069	19069	9330	
Bumped 1	1274	1354	1330	1293	423	
Bumped 2	334	342	364	346	93	
Bumped 3	121	121	137	114	50	
Bumped 4	49	47	49	54	12	
Bumped 5	27	23	19	10	5	
Bumped 6	7	12	9	11	4	
Bumped 7	6	7	5	6	1	
Bumped 8	3	2	2	2	2	
Bumped 9	1		7	0	1	
Overflow				4		Total
Total Free	19353	19211	19069	19069	9330	86032
Total Bumped	1822	1908	1922	1840	591	8083
					Percent	9%

The percentage of bumped ABR messages to total sent ABR messages increases slower than might be expected as the number of users is increased above the 100% capacity level. This is probably a result of the algorithm allowing ABR messages to be

sent, even when a reserved capacity level has a flag set to reserve it. The peculiar decrease in percent shown for 5000 users is most likely a result of the random nature of the data generation. It also appears from both the node capacity tables and the ABR tables, that none of the nodes appear to have an advantage or disadvantage over the other nodes as the number of users is increased. The algorithm developed for this part of the simulation, therefore, is an effective algorithm to maximize throughput for the wireless network.

4.3. Cell Loss--Buffering Results on the Backbone

The Third Part of the model simulation deals with data cell performance on the links of the wireless backbone. This model makes use of output buffers as described in Chapter 3. For this simulation, the output buffers are set at 1/10 the size of the available cell slots in a timing frame. This simulation takes relatively long periods of time since there are transactions generated for every ATM cell of each traffic type created. As a result, a few parameters were changed to make the simulation run time more manageable:

•Each link frequency bandwidth is now 3 MHz to force more discarded cells.

•The timings for the simulation were changed to a one hour initialization period and a 5 hour run.

4.3.1. Theoretical results

The way the traffic is routed after it is generated also had to be changed. Traffic generated from a node is no longer allowed to use the same node as a destination. Node 3 and Node 5 are not allowed to make connections to each other. These changes were

implemented in order to restrict the analysis to the links. The same destination determination blocks and path determination blocks that were used in Part 2 were used here with minor changes. Now if a request is routed to its own destination block, it is automatically routed to the next block in line. This has the effect of changing the routing capacity priorities as illustrated in Figure 23.

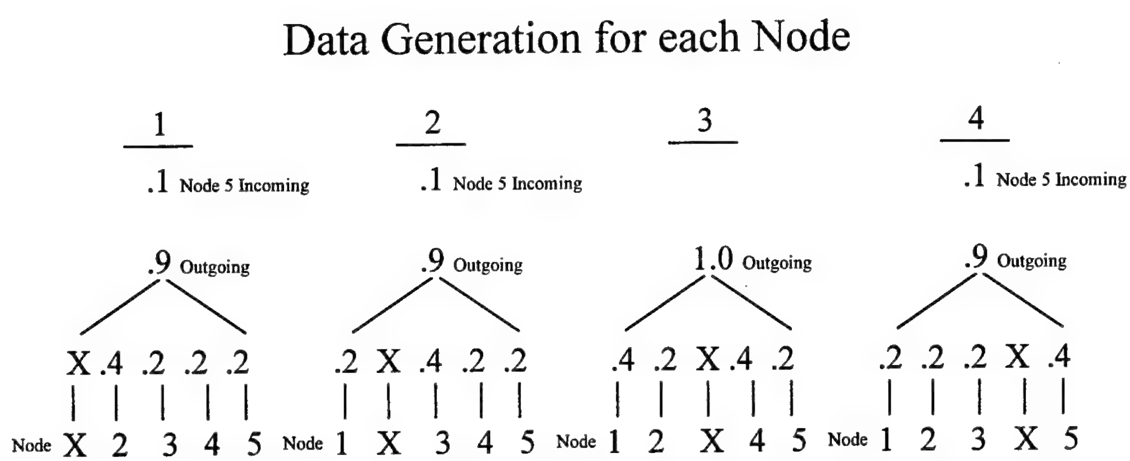


Figure 23: Traffic Routing Effects on Buffer Link Analysis

New capacity usage equations for Link A are:

$$\text{Left Link A} = (3\times.18\text{Outgoing Uplink}+.36\text{Outgoing Uplink}+.10\text{Incoming Uplink}+2\times.18\text{Incoming Uplink}+.36\text{Incoming Uplink})$$

$$\text{Right Link A} = (3\times.18\text{Outgoing Downlink}+.36\text{Outgoing Downlink}+.10\text{Incoming Downlink}+2\times.18\text{Incoming Downlink}+.36\text{Incoming Downlink})$$

Table 32: Buffer Link Analysis Total cells/day

	MHz Left	MHz Right	cells/sec/MHz	sec/day	cells/day
Left Link	3		7700	86400	1995840000
Right Link		3	7700	86400	1995840000

Table 33: Buffer Analysis Cells/day for each Link per User

cells/day/user	Left	Right
Link A	1224321.6	1224504.3
Link B	1615654.86	1616225.9
Link C	1224504.32	1224321.6

Table 34: Buffer Analysis Number of Users per Link Capacity

Link A

% Capacity	40	50	60	70	80	90	100
Left Link	652.06397	815.07996	978.0959513	1141.112	1304.12794	1467.143927	1630.15992
Right Link	651.96667	814.95833	977.9500002	1140.942	1303.93333	1466.925	1629.91667

Link B

% Capacity	10	20	30	40	50	60	70	80	90	100
Left Link	123.53133	247.06267	370.5940017	494.1253	617.65667	741.1880035	864.719337	988.25067	1111.782	1235.313
Right Link	123.48769	246.97538	370.4630738	493.9508	617.438456	740.9261475	864.413839	987.90153	1111.389	1234.877

Link C

% Capacity	40	50	60	70	80	90	100
Left Link	651.96667	814.95833	977.9500002	1140.942	1303.93333	1466.925	1629.91667
Right Link	652.06397	815.07996	978.0959513	1141.112	1304.12794	1467.143927	1630.15992

It is immediately apparent that the number of users is far less than they were for Part 2.

This system models an M/D/1/K queueing system. The M stands for Memoryless or Markov, and means a negative exponential inter-arrival time. The D means the service time is fixed or deterministic. The 1 means there is a single server, and the K means there is a finite queue. The utilization is defined as the number of arrivals per unit time times

the mean service time, $\rho = \lambda \cdot s$. Some equations dealing with CLP for an M/D/1/K system are [7]:

$$CLP \approx Q(x) = \exp\left[-2x\left(\frac{1-\rho}{\rho}\right)\right]$$

$$x = \frac{1}{2}\ln(Q(x))\left(\frac{\rho}{1-\rho}\right)$$

$$\rho = \frac{2x}{2x - \ln(Q(x))}$$

$Q(x)$ is the probability the queue size will exceed a number x.
ρ is the utilization.

These equations are only useful at high utilization rates. Since there were only three runs made in this simulation, 100, 200, and 300 users, there is insufficient data to compare. As an example, at 300 users and using the data from Table 34 for Link B with a buffer size of 27:

$$Q(x) = \exp\left[-2(27)\left(\frac{1-.24}{.24}\right)\right]$$
$$= 5.44 \times 10^{-75}$$

This is probably an unrealistic result. For our data runs we would expect to see few if any discarded cells.

4.3.2. Simulation results

Simulation runs were completed for 100 users, 200 users, and 300 users. There is no useful data collected here, however since the network is operating far below its

maximum utilization. There were no discarded cells or even buffered cells at these low rates. There was a run done at 1000 users, but the data is unreliable. There were some problems with the version of the program used for the simulation causing the requirement of manual input to keep the program running during frequent intervals of even these low numbers. This version of the program has a step count limit of $2^{31}-1$ and apparently this same limit is applied to variables as well. It can be observed in Table 35 that past 300 users, the numbers for packets passing without problem (Open B Left and Right) decreases instead of increases as should have occurred. Most likely the variables storing the values were incremented beyond the limit and they simply rolled-over and began again at zero. There is a newer version of GPSS available that fixes the step count problem, but not the variable roll-over problem. As the program does appear to follow its intended structure, follow-up work using the new version should produce useful data.

Table 35: Buffer Analysis Results

	Dump B Left	Dump B right	Buff B Left	Buff B Right	Open B Left	Open B Right
100 Users	-	-	-	-	43,144,374.00	43,150,132.00
200 Users						
300 Users	-				114,295,086.00	114,323,784.00
400 Users	-				23,490,626.00	23,497,689.00
1000 Users	44,550.00	39,927.00	190,071.00	194,102.00	58,102,567.00	58,103,475.00

Chapter 5

5. Conclusions

5.1. Summary of Results

Overall the results from the simulations are very encouraging. These were generally some very complex programs to implement the real system. The ALOHA reservation channel requires relatively few slots to be useful and therefore has little impact on the system capacity. The algorithm for Part 2 of the simulation is working efficiently. The majority of the available capacity is allocated in a manner which is fair and ensures that no calls will be blocked out indefinitely. For the data rates and message lengths defined, the useful level of capacity for the system is around 73% with approximately 1950 users per node. The critical link of the three links in this network is link B. This is a result of the link serving two nodes on one side and a node with a connection to the PSTN on the other side. Even with the increased traffic on this link, it still has greater capacity than the nodes. This means that normally the nodes will be the limiting throughput factor. It is possible that the frequency bandwidths may be divided up slightly better to give the nodes and the overall network more capacity. As the network becomes more congested as the number of users is increased, the vast majority of the ABR type traffic continues to be able to get through. The program developed to model this connection set-up for the entire network appears to work as designed since the actual model performance closely resembles the predicted performance. This is a powerful tool for analyzing wireless ATM networks and will undoubtedly be useful in the

future. Although there were problems running the buffering analysis program, it does appear to be working as it did complete at lower loads. The most important structure of the program, the generation of packets for a message request at the proper data rate and message length is working as it should. The step-count limit of the GPSS program will no longer be a problem with the newest version. This newer version of the program will enable use of the program at higher loads without having to constantly attend to the program. The roll-over tendency of the statistic gathering variables will have to be contended with in order to gather meaningful data. Once these bugs are worked out of the program, it too should be useful in determining capacity on the network. These figures can ultimately be used with Part 2 to determine connection decisions for different types of data requirements.

5.2. Areas for Further Research

5.2.1. Self-similar data traffic generation

Exponential distribution or Poisson distribution is a common way to model traffic patterns. Frequently, however, real traffic tends to deviate from this pattern and follow a pattern known as self-similarity. This means that traffic frequently appears to cluster and even the clusters appear to cluster. The result of this clustering is that a network design or ATM switch design may not have enough capacity to handle these clusters when they appear, especially since they are not predicted properly with the exponential distribution [18]. There is ongoing research studying this problem and it could be an interesting field to apply this to wireless ATM project.

5.2.2. Integration of mobile handoffs

So far analysis and modeling of this network have all been based on stationary users. Given the nature of the network being wireless, it would be advantageous to eventually integrate mobile users into the network as well. This brings up other issues that can be challenging to implement such as handoffs, station keeping, and security. Handoffs in particular can be difficult, especially depending on how quickly the user is moving from cell to cell. Implementing this problem into the models presented in this thesis might require writing a separate model and integrating it into these models. Undoubtedly, this will be an important issue to be addressed as the Summit County project gets closer to reality.

5.2.3. Types of traffic and demand

All of the traffic types in this model have been modeled to have constant data requirements. An important issue to address would be bursty type traffic, in particular for VBR. The burstiness nature of VBR can have a significant impact on the network, in particular with the output queues from the ATM switches. It can be possible to model the burstiness by implementing some type of a switch with the part of the buffer analysis program that generates the individual ATM cells. Whereas the master transaction is sent at the data rate to split off the ATM cells, it could randomly be assigned new data rates to affect the interval it generates the new ATM cells. This probably would not be too difficult to implement and could bring the analysis even closer to modeling a real system.

Another avenue to investigate is how different times of the day, week, or even year can have an impact on the demand placed on the network. Excess capacity can be a

costly expense so a network designer would strive to meet the demands with as little excess as possible. On the other hand, if there are too many times the network is unavailable to a new user for lack of capacity, the network will lose customers to other competitors or alternate means of communication. It is therefore, imperative for a successful designer to predict and be prepared for such changes in network demand.

5.2.4. The System Program

Finally, the parts of this system model can be integrated together. In particular, results from the buffering analysis can be used to determine how much capacity to allocate for different types of traffic when accepting new connections. The buffering analysis itself can be taken further to explore issues such as cell delay and jitter and their impacts on quality of service. Bandwidths of the uplink, downlinks, leftlinks, and rightlinks can be adjusted to allocate capacity in the best manner and avoid chokepoints. In short, the powerful tools developed in this thesis are only a starting point with which a great deal of simulation experimentation can come from.

References

[1] V.Garg, and J. Wilkes, *Wireless And Personal Communications Systems.* Upper Saddle River, NJ: Prentice Hall PTR, 1996, pp. 1-51, pp. 207-209.

[2] D. Goodman, "Cellular Packet Communications", *IEEE Transactions On Communications*, Aug. 1990, pp. 1272-1280.

[3] U.S. Department of Commerce, National Telecommunications and Information Administration, Survey of Rural Information Infrastructure Technologies, Sep. 1995, pp. 1-1 to 5-8.

[4] R. Ziemer, M. Wickert, D. Harvatin, R. West, T. Savage, "Summary for: Tradeoffs For Wireless Multimedia Transmission In Rural Environments", University of Colorado at Colorado Springs, Integrator Corp., Colorado Springs, CO, Spring 1997, pp. 1-5.

[5] A. Ayanoglu, K. Eng, and M. Karol, "Wireless ATM: Limits, Challenges, and Proposals", *IEEE Personal Communications*, Aug. 1996, pp. 18-33.

[6] O. Kyas, *ATM Networks*, Sheffield, U.K., International Thomson Publishing, 1995, pp. 130-138, pp. 147-148.

[7] J. Pitts and J. Schormans, *Introduction to ATM Design and Performance*, West Sussex, England, John Wiley & Sons Ltd., 1996, pp 1-12, pp. 26-29, pp. 63-65, pp. 92-95, p. 113-120, pp. 151-165.

[8] U. Black, *ATM: Foundation for Broadband Networks*, Englewood Cliffs, NJ, Prentice Hall, 1995, pp. 181-184.

[9] D. Minoli and T. Golway, *Planning and Managing ATM Networks*, Greenwich, CT, Manning Publications Co., 1997, pp. 15-16, pp. 38-48.

[10] D. McDysan, "ATM--Theory & Application", *IEEE Computer & Communications Societies--Pikes Peak Chapters Joint Presentation*, Colorado Springs, CO, Dec. 12, 1996.

[11] W. Stallings, *Data and Computer Communications*, Englewoood Cliffs, NJ, Macmillan Publishing Co., 1994, pp. 368-369, p. 829.

[12] A. Acampora, "Wireless ATM: A Perspective on Issues and Prospects", *IEEE Personal Communications*, Aug. 1996, pp. 8-17.

[13] A. Lymer, "Digital-Modulation Scheme Processes RF Broadcast Signals", *Microwaves & RF*, Apr. 1994, pp. 149-159.

[14] D. Raychaudhuri et al.,"WATMnet: A Prototype Wireless ATM System for Multimedia Personal Communication", *IEEE Journal On Selected Areas In Communications*, Jan. 1997, pp. 83-95.

[15] R. Garzia and M. Garzia, *Network Modeling, Simulation, and Analysis*, New York, Marcel Dekker, INC., 1990, pp. 1-16.

[16] Institute for Telecommunication Sciences, "Map Background from Map Database for Summit County", U.S. Dept. of Commerce, Boulder Laboratories, Visit on Jan. 9,1997.

[17] T. Savage, "Spreadsheet Data Supplied for OFDM Links", Integrator Corp., Colorado Springs, CO, Mar,1997.

[18] W. Stallings, "Viewpoint: Self-similarity upsets data traffic assumptions", *IEEE Spectrum*, Jan. 1997, p. 28.

Appendix

Details of Simulation Code

The simulations used in this system model are lengthy, particularly the connection admission control model. As a result, only a few items of interest are presented in this appendix. For full detail of the code itself, please refer to the programs on the disk supplied with this thesis. The source code files are .gps files that can be viewed with any text editor or word processing program. There are also some text files in the cac and buffer directories that are useful for generating multiple copies of certain portions of the code. The contents are:

Directory Aloha:

- Slots.gps
- NoSlots.gps

Directory buffer:

- Buffer.gps
- Datamstr.txt
- Donemstr.txt
- Initmstr.txt

Directory cac:

- Topo.gps
- Datamstr.txt
- Nodemstr.txt
- Nodecopy.txt

A.1. Reservation Channels

The programs modeling the reservation channels are both different and therefore are presented separately.

A.1.1. Slotted ALOHA

This is an example of how data requests are generated for all of the models. These blocks are fairly basic for this part of the model. The other parts assign several more parameter values to each transaction. For more detail on the slotted ALOHA code, please refer to Slots.gps on the disk.

```
*********************************************************************************
*Block Statements:
*********************************************************************************


***
*Generate the number of connection requests:
***
```

*Low Rate CBR:

```
GENERATE RVEXPO(1,&REQUEST(1)/(&USERS)),,,,,1PB,4PL
ASSIGN MSGTYPE,1,PB
ASSIGN BIRTH,AC1,PL
TRANSFER ,GOING                 Enters the transaction into the model.
```

*Medium Rate CBR:

```
GENERATE RVEXPO(2,&REQUEST(2)/(&USERS)),,,,,1PB,4PL
ASSIGN MSGTYPE,2,PB
ASSIGN BIRTH,AC1,PL
TRANSFER ,GOING                 Enters the transaction into the model.
```

*High Rate CBR:

```
GENERATE RVEXPO(3,&REQUEST(3)/(&USERS)),,,,,1PB,4PL
ASSIGN MSGTYPE,3,PB
ASSIGN BIRTH,AC1,PL
TRANSFER ,GOING                 Enters the transaction into the model.
```

*VBR:

```
GENERATE RVEXPO(4,&REQUEST(4)/(&USERS)),,,,,1PB,4PL
ASSIGN MSGTYPE,4,PB
ASSIGN BIRTH,AC1,PL
TRANSFER ,GOING                 Enters the transaction into the model.
```

*ABR:

```
GENERATE RVEXPO(5,&REQUEST(5)/(&USERS)),,,,,1PB,4PL
ASSIGN MSGTYPE,5,PB
ASSIGN BIRTH,AC1,PL
```

TRANSFER ,GOING — Enters the transaction into the model.

A.1.1.Pure ALOHA

This is an example of how variable for this program are initialized. The initialization areas of the other parts are much larger than this one. To look into the code for the pure ALOHA in greater detail, look and NoSlots.gps on the disk.

```
****************************************************************************
*Variable Initialization:
****************************************************************************

LET &USERS=100          The total users in the area.

LET &RQSTSIZE=64        Size of the request packet in bits.

LET &CHNLRATE=50        Datarate of the reservation channel in kilobits/sec.

LET &RESSLOTS=7         Reservation slots.

LET &FRAME=&RESSLOTS*(&RQSTSIZE/&CHNLRATE)     Timing frame size in ms.

LET &AVG(1)=2           The number of low rate CBR requests/day (audio).
LET &AVG(2)=.5            " medium rate CBR requests/day (low video).
LET &AVG(3)=.1            " high rate CBR requests/day (high video).
LET &AVG(4)=10            " VBR requests/day (data/browser traffic).
LET &AVG(5)=5             " ABR requests/day (e-mail).

LET &REQUEST(1)=(24*60*60*1000)/&AVG(1) Request rate of low CBR in ms/request.
LET &REQUEST(2)=(24*60*60*1000)/&AVG(2)     " medium CBR.
LET &REQUEST(3)=(24*60*60*1000)/&AVG(3)     " high CBR.
LET &REQUEST(4)=(24*60*60*1000)/&AVG(4)     " VBR.
```

```
LET &REQUEST(5)=(24*60*60*1000)/&AVG(5)       " ABR.

LET &INITTIME=1*60*60*1000 Time of the initialization run, hrs conv. to ms.
LET &FINITIME=5*60*60*1000 Time of the actual run, hrs converted to ms.

OUT1 FILEDEF 'files\mac\SLOTTXT.txt',APPEND
OUT2 FILEDEF 'files\mac\SLOTSHT.txt',APPEND
```

A.1. Connection Admission Control

This is an example of a Boolean variable. Boolean variables are very important for making decisions within the network. For more detailed code of this program, please refer to topo.gps on the disk supplied.

```
*****************************************************************************
*These boolean variables are used by a finishing transaction to free waiting
*transactions from BUSY if there is enough resources available for them.
*This check is for CBR/VBR waiting transactions:
FREECHK1 BVARIABLE (PR'E'10)*(((PF(ORIG)'NE'PF(DEST))*_
        (((((PF(QLINKA)'E'&CLNLINKA)*(PF(QLINKA)'NE'0))+_
        ((PF(QLINKB)'E'&CLNLINKB)*(PF(QLINKB)'NE'0))+_
        ((PF(QLINKC)'E'&CLNLINKC)*(PF(QLINKC)'NE'0)))*_
        (BV(FREELINK))*(((PF(DEST)'E'5)+((PF(DEST)'E'1)*_
        ((NOT(BV(QCHK11)))*(NOT(BV(QCHK21)))))+((PF(DEST)'E'2)*_
        ((NOT(BV(QCHK12)))*(NOT(BV(QCHK22)))))+((PF(DEST)'E'3)*_
        ((NOT(BV(QCHK13)))*(NOT(BV(QCHK23)))))+((PF(DEST)'E'4)*_
        ((NOT(BV(QCHK14)))*(NOT(BV(QCHK24))))))*((PF(ORIG)'E'5)+_
        ((PF(ORIG)'E'1)*((NOT(BV(QCHK1B1)))*(NOT(BV(QCHK2B1)))))+_
        ((PF(ORIG)'E'2)*((NOT(BV(QCHK1B2)))*(NOT(BV(QCHK2B2)))))+_
        ((PF(ORIG)'E'3)*((NOT(BV(QCHK1B3)))*(NOT(BV(QCHK2B3)))))+_
        ((PF(ORIG)'E'4)*((NOT(BV(QCHK1B4)))*(NOT(BV(QCHK2B4))))))))+_
        ((((PF(ORIG)'E'&CLNORIG)*(&CLNORIG'NE'5))+_
        ((PF(ORIG)'E'&CLNDEST)*(&CLNDEST'NE'5))+_
        ((PF(DEST)'E'&CLNORIG)*(&CLNORIG'NE'5))+_
        ((PF(DEST)'E'&CLNDEST)*(&CLNDEST'NE'5)))*_
```

```
(BV(FREELINK))*(((PF(DEST)'E'5)+((PF(DEST)'E'1)*_
((NOT(BV(QCHK11)))*(NOT(BV(QCHK21)))))+((PF(DEST)'E'2)*_
((NOT(BV(QCHK12)))*(NOT(BV(QCHK22)))))+((PF(DEST)'E'3)*_
((NOT(BV(QCHK13)))*(NOT(BV(QCHK23)))))+((PF(DEST)'E'4)*_
((NOT(BV(QCHK14)))*(NOT(BV(QCHK24))))))*((PF(ORIG)'E'5)+_
((PF(ORIG)'E'1)*((NOT(BV(QCHK1B1)))*(NOT(BV(QCHK2B1)))))+_
((PF(ORIG)'E'2)*((NOT(BV(QCHK1B2)))*(NOT(BV(QCHK2B2)))))+_
((PF(ORIG)'E'3)*((NOT(BV(QCHK1B3)))*(NOT(BV(QCHK2B3)))))+_
((PF(ORIG)'E'4)*((NOT(BV(QCHK1B4)))*(NOT(BV(QCHK2B4))))))))))+_
((PF(ORIG)'E'PF(DEST))*_
((PF(ORIG)'E'&CLNORIG)+(PF(ORIG)'E'&CLNDEST))*_
(((PF(ORIG)'E'1)*((NOT(BV(QCHK31)))*(NOT(BV(QCHK41)))))+_
((PF(ORIG)'E'2)*((NOT(BV(QCHK32)))*(NOT(BV(QCHK42)))))+_
((PF(ORIG)'E'3)*((NOT(BV(QCHK33)))*(NOT(BV(QCHK43)))))+_
((PF(ORIG)'E'4)*((NOT(BV(QCHK34)))*(NOT(BV(QCHK44))))))))
```

A.1. Backbone Buffering Analysis

This is an example of the code used to split off the ATM cells from the master transaction. It is the heart behind creating the cells of a message at the data rate of the message. For further details, please refer to buffer.gps on the disk supplied.

```
***************************
*Assignment Control Blocks:
***************************

*Section for Splitting the Request Cell into Send and Reply ATM Data Cells.

*BEGINSPLIT

CKASSIGN TEST NE PB(MSGTYPE),5,SPLOTOD1 Do not split if ABR.
 SPLIT 1,SPLDTOO1,MBRNUM$PF 1 for each direction between orig & dest nodes.

*If VBR, this TEST sequence will assign the orig to dest nodes direction a
```

```
*message length number of cells and datarate 1/10th the dest to orig nodes
*direction since downloaded data is usually much greater than uploaded
*requests.
 TEST E PB(MSGTYPE),4,SPLOTOD1
 ASSIGN MSGLNGTH,FIX(.1*PF(MSGLNGTH)),PF
 ASSIGN MSGRATE,10*PL(MSGRATE),PL

*This sequence will split the original packet into the total message length
*size number of ATM cells for the message in the orig to dest node direction.
SPLOTOD1 SPLIT 1,VPISNDA1,MBRNUM$PF Send next ATM cell of message.
 ASSIGN MSGLNGTH-,1,PF
*If its the last packet, advance then send.  Otherwise repeat split.
 TEST E PF(MSGLNGTH),1,SPLOTOD2
 ADVANCE PL(MSGRATE)
 ASSIGN MBRNUM,0,PF
 TRANSFER ,VPISNDA1
SPLOTOD2 ADVANCE PL(MSGRATE) Pause to satisfy datarate.
 TRANSFER ,SPLOTOD1

*This sequence will split the original packet into the total message length
*size number of ATM cells for the message in the dest to orig node direction.
*First reverse the directions of the links originally set.
SPLDTOO1 ASSIGN TEMP,PF(ORIG),PF
 ASSIGN ORIG,PF(DEST),PF
 ASSIGN DEST,PF(TEMP),PF
 TRANSFER ,FINDPATH Set the links, then return.
SPLDTOO2 ASSIGN TEMP,PF(ORIG),PF
 ASSIGN ORIG,PF(DEST),PF
 ASSIGN DEST,PF(TEMP),PF
SPLDTOO3 SPLIT 1,VPISNDA1,MBRNUM$PF Send next ATM cell of message.
 ASSIGN MSGLNGTH-,1,PF
*If its the last packet, advance then send.  Otherwise repeat split.
 TEST E PF(MSGLNGTH),1,SPLDTOO4
 ADVANCE PL(MSGRATE)
```

```
 TRANSFER ,VPISNDA1
SPLDTOO4 ADVANCE PL(MSGRATE) Pause to satisfy datarate.
 TRANSFER ,SPLDTOO3

*ENDSPLIT
```